

Chapter 5

TRANSPORTATION SECTOR

5.1 INTRODUCTION

The trend of more than a decade of continuous energy-efficiency improvements in transportation, marked by a sharp decoupling of energy consumption and economic growth, appears to have come to an end. The transportation sector's energy use now appears to be growing at nearly the same rate as the gross domestic product (GDP).

From 1949 until 1973, energy use in the U.S. transportation sector grew at an average annual rate of 3.6% per year (EIA, 1996a, Table 2.1). In the years following the oil crisis of 1973-74 until the oil price collapse of 1986, that rate fell to only 0.6% per year.¹ This sharp decrease in growth was caused by a combination of market and non-market factors – sharply rising oil prices and, perhaps more important, strong expectations that prices would continue to escalate for the foreseeable future; threats of gasoline rationing and actual (though largely government-caused) local gasoline shortages; successes in government-sponsored R&D, especially in aeronautics; and new regulations, particularly the Corporate Average Fuel Economy (CAFE) standards for automobiles and light trucks. Some manifestations of the decrease in the growth of energy use during this period were:

Between 1973 and 1988, new passenger cars increased their fuel economy from about 14 MPG to 28.6 MPG (EPA rated) (Heavenrich and Hellman, 1996, Table 1), a rate of 5% per year.

During 1970-1987, commercial aviation decreased in energy intensity from 10,351 Btu per passenger-mile to 4,753 Btu/pm (Davis and McFarlin, 1996, Table 2.16) again at an average rate of 5% per year.

During 1970-1994, the energy intensity of rail freight decreased from 691 Btu/ton-mile to 388 Btu/ton-mile, or 44% (Davis and McFarlin, 1996, Table 2.17), a rate of 2.4% per year.

Although changes in travel behavior, choice of vehicle size, changes in vehicle occupancy rates and other non-technological factors have a role in the rate of growth in transportation energy use, improved technological efficiency has been the most critical factor in energy trends. For example, had energy intensities not changed since 1972, commercial airlines would be using over twice the energy they use today (assuming today's number of passenger-miles of travel), and three quarters of the savings are due to technological improvements in aircraft (Davis and McFarlin, 1996, Table 2.21). Similarly, examination of the causes of substantial fuel economy gains by automobiles during the 1970s and 1980s show that the majority of the gains were achieved by improving technical efficiency, not by consumers moving to small cars. Between 1978 and 1984, only 7.8% of the period's MPG gain was achieved by shifts to smaller cars (Westbrook and Patterson, 1985). Between 1976 and 1989, the combination of weight reduction, improved transmissions, tires, and aerodynamics, widespread use of fuel injection, various engine improvements, improved lubricants, and wider use of front wheel drive accounted for about 70% of the total 8.4 MPG improvement during the period (Westbrook, 1989). In fact, the technology of automobiles has improved so much over the past few decades that if the 4,000 pound plus, 15.8 MPG automobile of 1975 were to be built with today's technology but *without any change in weight or horsepower*, it would get 26.4 MPG (Greene and Fan, 1994)! And although 85% of the improvement in rail freight energy efficiency came from increased loadings per car, much of the 85% resulted from improved communications and computing capability (other factors included changing composition of freight during this period and other operational improvements), and improved vehicle technology accounted for the remaining 15% (Greene, 1996).

Over the past ten years (1986-1996), the rate of growth of transportation energy use has averaged 1.6% per year, but in the past three years it accelerated to 2.2% per year, just below the rate of growth of GDP. Transportation energy efficiency, which improved significantly during the decade of the 1980s, appears to be stagnant (U.S. DOT/BTS, 1996, p. 87). The average fuel economy of new passenger cars has not improved significantly over the past decade. The average fuel economy of light-duty vehicles, new cars, and light trucks combined has not changed significantly since 1982 (Heavenrich and Hellman, 1996, Table 1) and, as a consequence, the average on-road fuel economy of the entire on-road light-duty vehicle fleet was only 1% higher in 1995 (the most recent year for which data are available) than in 1991 (U.S. DOT/FHWA, 1996, Table VM-1). Gasoline prices are now at pre-1973 levels and fuel economy standards have not been raised over 1985 levels. There are exceptions, however: commercial air travel and rail freight continue to make meaningful efficiency gains (U.S. DOT/BTS, 1996, p. 101). Overall, the transportation sector appears to have entered a period of growth in activity only slightly slower than that of GDP with only modest gains or no improvement in energy efficiency.

Despite these recent trends, the 1997 Annual Energy Outlook (AEO97) reference case forecast to 2015, which serves as the backdrop for this analysis, foresees very slow growth in transportation energy use (1.4%/yr.) accompanied by virtually no change in the prices of transportation fuels (0.2%/yr.). A modest rate of growth in vehicle travel (1.4%/yr.) together with MPG gains of 5.1 MPG for new passenger cars and 3.7 MPG for new light trucks over 1995 levels, combine to hold the growth of light-duty vehicle energy use to 1% per year through 2015. Every year since at least 1989, the AEO (among others) has forecasted continued light-duty vehicle fuel economy gains yet the actual fuel economy of light-duty vehicles as a whole has not improved. In some cases, energy prices have turned out to be lower and in other cases higher than expected. Apparently, technology that could have been used to improve fuel economy is either not being implemented, or is being used to provide some other feature that consumers value, such as performance. We expand on this point below in explaining why, in our "business-as-usual" (BAU) case, we forecast no improvement in light-duty vehicle fuel economy. We believe that, given low energy prices, plentiful oil supplies, no market disruptions, and no new energy policy initiatives, it is optimistic to expect continued energy-efficiency improvement and slow growth of energy use.

Current policy initiatives and activities to increase future transportation energy efficiency are relatively modest. Except for light-duty highway vehicles, the federal government does not regulate transportation fuel efficiency. The National Highway Traffic Safety Administration has the power to raise CAFE standards for autos and light trucks, but there seems little chance that it will do so at the present time. The Energy Policy Act contains provisions to move alternative fuel vehicles into the fleet (fleet vehicle requirements and altfuel tax credits), but these provisions are limited, and congressional support for coercive action is nonexistent. On the other hand, there are important R&D initiatives that could play a role in improving transportation fuel efficiency, particularly the long-standing NASA and Defense Department programs in aeronautic design and the Partnership for a New Generation of Vehicles (PNGV), a joint government/industry research effort aimed primarily at developing vehicles with up to three times current fuel economy levels.

The newest of federal initiatives aimed at improving transportation fuel efficiency, PNGV has reorganized and redirected the federal government's R&D effort in advanced automotive technologies towards the ambitious goal of tripling automotive fuel economy and reducing pollutant emissions while at the same time preserving consumer amenities and holding down costs. Current PNGV spending is on the order of \$250 million dollars (the exact amount is subject to debate because of definitional problems of which efforts are actually dedicated to PNGV goals) (U.S. Congress, OTA, 1995), with the largest government share coming from DOE's Electric and Hybrid Vehicle Program. Current PNGV thinking seems aimed at an advanced hybrid-electric vehicle, with research efforts aimed particularly at advanced materials, high-power energy storage devices, fuel cells and improved engines, lean NO_x catalysts (to allow necessary emission control for lean-burn engines including diesels and direct injection stratified charge engines), and improved electric drives, including power electronics.

In this chapter, the potential for these and other energy-efficient and low-CO₂ technologies to cost-effectively reduce transport sector greenhouse gas emissions is examined. Three transportation sector scenarios were

developed using the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) model, AEO97 version (see Overview of Methodology box), with reference case assumptions about macroeconomics and energy prices (Decision Analysis Corp., 1996; EIA, 1994). These are labeled the (1) "business-as-usual" (BAU), (2) "efficiency" (EFF), and (3) "high-efficiency/low-carbon" (HE/LC) cases. Our business-as-usual case differs from the AEO97 reference case only in that new light-duty vehicle fuel economy is held constant at current levels throughout the period of the forecast. In the reference case, it improves at an average annual rate of 0.4%.

The efficiency and high-efficiency/low-carbon scenarios differ from each other less in effort than in outcome. In our view, the improvements postulated in the efficiency scenario are *likely* to be forthcoming if appropriate policy measures are undertaken and research efforts intensified. In contrast, because the outcomes postulated in the high-efficiency/low-carbon scenario require technological breakthroughs, they require a certain degree of luck to be achieved by 2010. There are no credible methods to accurately gauge the probability of such breakthroughs; we believe they stand a decent chance of occurring with an intensification of research efforts, but we stop short of claiming that they are a likely outcome of such an intensification. In other words, the efficiency scenario represents what is often called a "most likely" or "probable" scenario, in the authors' judgment. The high-efficiency/low-carbon scenario is better described as an "optimistic" or "possible" scenario. However, both are predicated on a major intensification of R&D effort plus significant policy measures aimed at pushing the market towards giving fuel efficiency a much higher priority.

The efficiency scenario is created by assuming earlier introduction of advanced fuel economy technology and by adding certain key technologies that are absent from the AEO97 reference case. It assumes the introduction of advanced ethanol-from-biomass technology in 2005, technology which the U.S. DOE is currently intensively involved in developing. In the efficiency case, technology development is incremental rather than revolutionary. Nonetheless, the efficiency case does presume a major energy technology R&D effort, perhaps two to ten times the level of current government programs. It also assumes that policies necessary to draw energy-efficiency technology into the market are implemented, as needed. In other words, effective policy actions, whether they be increased fuel economy standards, revenue neutral feebates, fuel taxes, public information or some other initiative, are assumed to have been put in place. This point is critical, because AEO97 forecasts inexpensive, plentiful fossil fuels, and because the goal of preventing global climate change is a classic public good that markets on their own will generally ignore.

Overview of Methodology

Producing scenarios for this analysis comprised three principle steps: (1) developing assumptions about future advances in energy technology for transportation, (2) entering these assumptions into an integrating model to predict their market acceptance and impact on transportation energy use and, (3) adjusting the model's predictions for analyses and forecasts done "on the side." Because of time and budget constraints, no attempt was made by the transportation sector team to integrate our scenarios with those of other energy-using sectors to produce an economy-wide scenario. The methodology is therefore a partial analysis of the effects of technology on the transportation sector, assuming no interaction with other sectors of the economy.

Obviously, there is no sure way to predict the evolution of technology. Thus, the key to developing a useful technology scenario is clearly documenting assumptions, and also demonstrating that the assumptions are consistent with recent advances in technology by referencing published scientific and technical reports. Wherever possible, we base our assumptions on objective technology assessments, such as the Office of Technology Assessment's (1995) examination of the potential for advanced automotive technology. The result of this step is a list of specific technologies with the following data for each, (1) date of initial market introduction, (2) quantitative impact on energy efficiency (e.g., % fuel economy improvement over a baseline vehicle) and, (3) incremental cost to the buyer.

We used the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS), Transportation Sector Model as a tool for integrating the technology assumptions and predicting their impact on energy use. NEMS is undoubtedly the most fully documented (U.S. DOE/EIA, 1994; 1995a, 1995b, 1996a, 1996b), most rigorously peer reviewed (e.g., NRC,) and most thoroughly tested comprehensive, national energy model. The NEMS Transportation Sector Model comprises a set of submodels for each transport mode that range in complexity from the highly detailed light-duty vehicle model to much simpler models for waterborne transport and rail freight.

The NEMS light-duty vehicle model requires an itemization of each technology, as well as its applicability to each of six passenger car and six light truck classes. In addition to introduction date, cost and fuel economy improvement potential, interactions (incompatibilities, complementarities, etc.) among technologies must be carefully specified. NEMS predicts market penetration over time based on cost-effectiveness and time since introduction, but also by applicability and interactions with other technologies. These predictions reflect normal requirements for testing of new technologies, as well as turnover of the stock of manufacturing capital. The Freight Truck and Air Travel Models also require a list of technologies, introduction dates and efficiency improvement estimates, but market penetration is handled somewhat more mechanistically. In both cases, new technologies are introduced when the price of fuel crosses a threshold price. For Rail Freight and Waterborne Freight, one must directly specify a rate of efficiency improvement.

Given technology assumptions, other macroeconomic inputs, and the energy and economic predictions of the 1997 Annual Energy Outlook Reference Case Projection, the NEMS Transportation Model predicts new vehicle sales, used vehicle scrappage, vehicle utilization, and fuel consumption by model and vehicle type. These endogenous predictions are sensitive to economic variables. For example, improving energy efficiency will result in some degree of increased vehicle travel due to the lower cost of fuel per mile. Based on the composition of demand by fuel type, NEMS also forecasts carbon emissions, as well. For the largest transport modes, the evolution of vehicle stocks over time are explicitly calculated in great detail. In general, the technological characteristics of a vehicle are determined in the year in which it is manufactured. NEMS then exhaustively accounts for the numbers of vehicles by type, class, and vintage, as well as which technologies have been applied to these vehicles. As a result, NEMS's representation of the dynamics of technological change are quite meticulous.

Finally, two parts of the scenario analysis were done "off line" thus necessitating some straightforward adjustments to the NEMS forecasts. The estimation of market supply and demand for cellulosic ethanol as a blending component of conventional gasoline was calculated by means of a spreadsheet model. The supply and demand studies upon which this analysis were based were simply too recently produced (they are based on draft reports) to have already been incorporated by the EIA into the NEMS model structure at the time. Also, we chose to introduce advanced direct injection diesel passenger cars and light trucks using the NEMS model algorithm for conventional gasoline vehicles rather than as alternative fuel vehicles. This reflects our belief that the new advanced diesels will be almost indistinguishable from gasoline vehicles from the consumers' perspective (with the exception of their cost and fuel economy, variables the NEMS model takes into account). A drawback of this choice is that we sacrificed the NEMS model's ability to automatically account for the additional diesel use and, therefore, had to adjust for it after the fact. Several additional calculations were made based on NEMS outputs. The NEMS model's output includes the market penetration of each technology by vehicle type and class. Using this information together with the input assumptions about technology costs and fuel economy improvement we were able to compute measures of the overall cost-effectiveness of the sum total of all technologies applied to passenger cars and light trucks.

The high-efficiency/low-carbon case begins with the efficiency case assumptions and then goes beyond incremental technological advances and postulates breakthroughs in fuel cell technology for light-duty vehicles, as well as major aerodynamic and engine efficiency gains for commercial aircraft, among other selected technological achievements. It also includes more optimistic assumptions about biomass ethanol production costs. It is not the intent of this scenario to include all possible technological advances, but rather to focus on a few that could have major long-run implications for greenhouse gas emissions from the transportation sector. We could, as well, have assumed technological breakthroughs for battery-electric or compressed or liquefied natural gas vehicles, both of which have some potential to reduce carbon emissions compared to petroleum-based fuels. The more breakthroughs one assumes, however, the lower the probability that the scenario will actually occur. Furthermore, in the long-run, no single technology appears to have a greater potential to reduce carbon emissions from transportation than the fuel cell. We do not assume a target and tradeable permit system equivalent to \$50/T of carbon in the high-efficiency scenario. We do assume in both scenarios that significant policies similar to this are in place to encourage producers to produce and consumers to choose fuel-efficient, low-carbon technologies.

Although the focus of this study is on the year 2010, forecasts to 2015 are also presented because changing the technology of transportation energy use takes more than one decade. Once a technology is market ready, two to three years of testing and certification are still required prior to introduction. Even then, most technologies will not appear on all makes and models simultaneously due to the need to replace plant and equipment in an efficient manner. Finally, expected lifetimes for transportation vehicles are counted in decades. The median expected lifetime of a passenger car is now 14 years, truck lifetimes average 16 years, marine vessel and aircraft life expectancies are at least twice that (Davis and McFarlin, 1996, Tables 3.6 and 3.7). Thus, the full impact of technologies introduced between now and 2010 will not be apparent in 2010. We include the year 2015 to illustrate this fact. In all cases, a normal rate of replacement of capital stock is assumed, both in the production of transportation vehicles and in their purchase and scrappage. That is to say, no changes are made to the NEMS model to accelerate the turnover of capital stocks.

Results of the three scenario projections are compared with EIA's AEO97 projections in Table 5.1. In the business-as-usual case, transportation energy use grows from 25.5 quads in 1997 to 32.3 quads in 2010 and to 34.0 quads in 2015. Emissions of carbon increase as well, up 26% in 2010 and 33% higher by 2015. The efficiency scenario achieves roughly a 10% reduction in energy use and a 12% reduction in transportation sector emissions versus the business-as-usual case by 2010. Reductions in 2010 versus the AEO97 reference case are slightly less, 7% for energy and 9% for carbon emissions. Use of cellulosic ethanol as a blending component in gasoline reduces greenhouse gas emissions by 2-3% over and above the reduction in energy use. The greatest reductions in fossil fuel use are achieved by rail freight (-16%), light-duty highway vehicles (-12%), and commercial air travel (-11%). Energy use in 2015 is actually below that of 2010 in the efficiency scenario because of the greater penetration of new, efficient equipment into the stocks of transportation vehicles. Transportation uses 28.2 quads of energy, 17% below the business-as-usual case but still 10% over 1997 levels. Emissions of carbon are down by 20% over the business-as-usual case, still 6% higher than in 1997. The high-efficiency/low-carbon scenario reduces energy use and carbon emissions by another 4% in 2010 and by an additional 5% in 2015. By 2015, transportation sector carbon emissions are projected to be below the 1997 level in the high-efficiency/low-carbon scenario.

Table 5.1 Comparison of Three Transportation Energy Scenarios to the AEO97 Reference Case

Energy Use (quads)			
	1997	2010	2015
Business-as-Usual	25.5	32.3	34.0
Reference Case	25.4	31.4	32.3
Efficiency	25.4	29.2	28.6
High-Eff/Low-Carbon	25.3	27.8	26.4
Carbon Emissions (MtC)			
	1997	2010	2015
Business-as-Usual	487	616	646
Reference Case	485	598	614
Efficiency	485	543	532
High-Eff/Low-Carbon	484	513	485

Note: Carbon emissions include emissions from the generation of electricity for electric vehicles. Reference case assumptions about electric vehicle market penetration have not been changed in any of the three scenarios. Similarly, transportation energy use includes electricity generation losses.

We wish to emphasize that, in our judgment, the reductions in carbon emissions described in these scenarios are unlikely to be achieved by advances in technology alone, in the absence of meaningful additional policy measures to insure that cost-effective and near cost-effective technologies to improve energy efficiency and to expand the production of biomass fuels are in fact implemented. This is not only our conclusion. The 1995 Asilomar Conference on Energy and Sustainable Transportation, organized by the National Research Council (NRC), Transportation Research Board's Committees on Energy and Alternative Fuels, addressed the question, "Is technology enough to achieve sustainable transportation?" The conference's consensus, to be published in a forthcoming volume of proceedings, was that technologies capable of creating a sustainable transport system could be developed over a reasonable time period but that the marketplace on its own would be unlikely to adopt such technologies in the absence of specific policy measures to make it happen (McNutt et al., 1997). Because of the inertia inherent in the nation's transportation system, and because reducing greenhouse gas emissions is a public good, meaningful policy action is likely to be essential to achieving the carbon emissions reductions described in these scenarios.

We also believe that research and development of low-carbon emission technologies will have to be expanded to achieve the results of the efficiency and high-efficiency scenarios. Support for this view can be found in the NRC's just-published review (NRC, 1997) of the research program of the PNGV, the most significant national effort to advance technology to improve transportation energy efficiency. The views of the standing committee charged with reviewing the progress of the program are unambiguous:

"The PNGV is experiencing severe funding and resource allocation problems that will preclude the program from achieving its objectives on its present schedule if they are not resolved expeditiously."

The panel comments on the serious underfunding of PNGV in at least nine different places in its report. In Table H-1, summarizing its assessment of the status and prospects for the key PNGV technologies, all technologies save fuel cells were categorized as having a basic need for additional resources. Noting that PNGV has been unresponsive in providing the committee with estimates of the funding that would be required, the committee notes that the industry consortium of the PNGV stated that it would like to see government funds

available to PNGV doubled (NRC, 1997, p. 107). Elsewhere, the committee notes that funding for ultracapacitor research would have to be increased by at least ten times for a period of 10 to 15 years in order to catch up with the status of battery research with respect to PNGV goals. While the technological progress assumed in our efficiency case does not require that PNGV goals are attained, continued advances by industry and government R&D programs will be essential. PNGV, of course, addresses only light-duty vehicles. R&D support for low-greenhouse gas technologies for other modes is even more modest. In the view of the transportation sector analytical team, substantial additional funding for R&D will be required, perhaps two to ten times what is presently being spent, depending on the area of investigation.

5.2 PROVEN AND ADVANCED TECHNOLOGIES

Despite the fact that the fuel economies of successive model years of U.S. new cars and light trucks have been essentially constant for the past decade (Heavenrich and Hellman, 1996), technologies positively affecting vehicle efficiency have continually entered the fleet. These include fuel injection, 4-valve per cylinder engines, 4-speed electronically controlled automatic transmissions with lockup, growing use of lightweight materials and structural redesign for weight reduction, tires with lower rolling resistance, and improved aerodynamics. Efficiency improvements offered by these technologies have been counteracted, however, by increased acceleration performance and top speed; weight increases due to increased body stiffness and more power and safety equipment (e.g., air bags); and other factors. In other words, auto makers and purchasers have been willing to trade off fuel economy for competing vehicle amenities such as weight and power.

There is wide agreement that new efficiency technologies will continue to enter the fleet, and that technologies recently entered will gain market share. Table E.1 in Appendix E lists those technologies that appear in the NEMS data base and are expected to either gain market share or enter the market during the next decade or so. With a few exceptions, these are proven technologies whose costs and impact on efficiency can be reliably specified. The most important of these technologies, from the standpoint of their potential impact on fleet fuel efficiency during the next few decades, are described briefly below. Documentation for costs and projected fuel efficiency improvements for these and the other technologies in the NEMS data base is contained in Energy and Environmental Analysis, Inc. (1994).

5.2.1 Material Substitution

Weight reduction has been a key factor in the U.S. automobile fleet's fuel economy improvement since the early 1970s, and will likely play an important role in future improvements. Past weight reductions involved a combination of a widespread conversion to front-wheel drive, which eliminated the drive shaft and rear axle and allowed important packaging gains; a significant downsizing of the fleet, made possible by changing consumer demands; the shift to unit body construction from a chassis on frame structure; and material substitution, largely from plain carbon steel to high strength low alloy (HSLA) steels, but also including shifts to plastic parts and some aluminum as well. Recently, structural redesign using supercomputers has allowed significant weight savings. However, much of these savings have been taken back by increases in body rigidity, which enhances ride quality and safety, as well as the addition of safety and power equipment. Accordingly, the average weight of the fleet has begun to increase.

Despite past improvements, there remain substantive possibilities for large weight reductions without sacrificing vehicle interior space or safety. The Office of Technology Assessment (U.S. Congress, OTA, 1995)² identified an array of weight reduction scenarios including the following: a "clean sheet" design using advanced steel alloys that might achieve greater than a 10% weight reduction in a mid-sized auto; all-aluminum vehicles using successively more optimized designs achieving up to a 30% reduction; and a technically-optimistic design using polymer composites achieving a 35-40% reduction (though OTA considered this last scenario to be quite uncertain from a commercial standpoint because it requires breakthroughs in manufacturing technology).

Material substitution is treated in a series of steps in the NEMS model, with each step representing a 5% weight reduction relative to the baseline. The first step (now complete in the current new car fleet) represents increased use of HSLA, while the next four steps represent increasing use of plastics and aluminum over time, to achieve a total reduction of 20% relative to a modern 1990 vehicle (more with older non-unit body designs).

5.2.2 Aerodynamic Drag Reduction

Improvements in vehicle aerodynamics have been an important part of the overall fuel economy improvement of the U.S. light-duty vehicle fleet, with average drag coefficients (C_d s) being reduced from 0.45-0.50 in 1979/1980 to between 0.30 and 0.35 today, with some models in the 0.27-0.29 range. These reductions are important to vehicle fuel economy because a 10% reduction in C_d typically will yield a 2.0-2.5% increase in fuel economy at constant performance.

Prototypes with extraordinarily low C_d s (e.g., 0.18 for the Chevrolet Citation IV and 0.15 for the Ford Probe IV ("Going with the Wind," 1984)) have been shown, and the General Motors EV1 electric car attains a C_d of 0.19. There is a strong consensus among auto makers, however, that mass market vehicles will likely be limited to C_d s of about 0.25 because of limits on the practical slope of windshields, need for cargo space (low C_d s require tapered rear ends), and other factors, including customer design preferences. Further, reductions in C_d s for light trucks are limited by factors such as need for high ground clearance and large tires, open beds in pickup trucks, and so forth. Also, the short length of subcompact autos limits the degree to which their C_d can be reduced.

In NEMS, aerodynamic drag reduction is also implemented in a series of steps starting from a 1990 C_d baseline of 0.37, with each step representing a 10% reduction over the previous level (i.e., to 0.33, 0.30, 0.27, and 0.245, respectively).

5.2.3 Improved Automatic Transmissions

A range of potential improvements to automatic transmissions can offer fuel economy benefits of up to about 6% in automobiles. Key areas of improvement are design changes that reduce hydraulic losses in the torque converter and transmissions with added numbers of gears, with continually variable transmissions possible.

Five-speed automatic transmissions were introduced in Japan and Europe a few years ago and have recently been introduced to the United States in a few luxury models. Nissan and Mercedes have experienced fuel economy gains over a 4-speed automatic in the 2-3 MPG range (Hattori et al., 1990). A number of continuously variable transmissions (CVTs) have been tested with widely varying results, and Subaru sells a small car with a CVT in the U.S. market. OTA estimates that a CVT should be capable of achieving approximately a 6% fuel economy increase over a 4-speed automatic.

Electronic transmission control of both conventional automatic transmissions and CVTs will add some benefits over the older mechanical controls. First generation controls selected only the shift points and provided about 0.5% benefit in fuel economy, and such controls were in most transmissions by 1995. More advanced second generation controls have appeared, and they interact with the engine control to optimally select torque converter lock-up and shift points while also determining engine calibration. Such controls provide 1.5% benefit over mechanical controls.

5.2.4 Engine Friction Reduction

Reducing mechanical friction is an ongoing process in engine development, and steady reductions in friction have occurred as engine designers continually modify existing engines and introduce new engine families.

There is substantial potential for fuel economy gains as existing friction reduction improvements are rolled into the fleet. Primary areas for further improvement are:

Piston and connecting rod weight reduction using lightweight materials,

Lightweight valves and valve springs,

Use of two rings instead of three,

Improved oil pumps,

Improved lubricants,

Low friction crankcase seals, and

Roller cam followers.

Only roller cam followers and two-ring pistons are discrete technologies, with specific benefits of 2% in fuel economy, while other benefits are based on design evolution.

Fuel economy improvements of as much as 4.5% (compared to current engines) should be available using the full range of evolutionary technologies. The NEMS model has separate representation of roller cams, while all other technologies are modeled as engine friction reduction in discrete steps of 1.5% benefit in fuel economy, with steps in the order of increasing cost and complexity.

5.2.5 Variable Valve Timing

In conventional engines, the timing and extent of opening of the intake and exhaust valves are fixed, and are compromises between the very different needs of high and low power settings. Variable valve control allows substantial efficiency improvement; for example, closing the intake valves early can substitute for throttling to reduce air intake, thus reducing pumping losses at low load. Also, variable valve control boosts engine power, allowing engine downsizing while maintaining power levels.

Honda uses a system called VTEC that controls both lift and timing of intake and exhaust valves. VTEC is not a fully variable system, offering only two settings for valve timing and lift, but it still obtains an 8% fuel economy improvement at constant performance. It has been used in the U.S. market both for boosting power (Acura NSX, Prelude VTEC) and improving fuel economy (Civic VX).

Although VTEC was introduced to the U.S. market in 1991 (in the NSX), neither VTEC nor competing systems (Mitsubishi uses a system, MIVEC, that combines valve control with cylinder shutdown at low loads) have gained significant market share since then. The major concerns are cost and complexity. Second generation VVT systems that offer wider control of lift and timing are expected to increase fuel economy benefits at constant performance to 10%.

5.2.6 Lean-Burn Engines

Lean-burn engines reduce engine power by reducing fuel flow without throttling back airflow, thus increasing the air/fuel ratio; in contrast, conventional engines maintain air/fuel ratios at or below "stoichiometric" (i.e., the ratio – about 14.6:1 – where there is just enough air to fully combust the fuel). Aside from the reduced pumping loss obtained by foregoing throttling, engine thermal efficiency is increased and hydrocarbon and carbon monoxide emissions are reduced. The primary challenges facing lean-burn engines are difficulties in maintaining stable combustion at high air/fuel ratios and the need to develop new NO_x catalysts that will work

in an oxygen-rich exhaust environment. The former challenge generally is handled by designing the cylinder/piston/valves/fuel injector system and operation in such a way as to stratify the fuel charge so the region around the spark plug has a richer fuel mixture than in the rest of the combustion chamber and ignites readily. An alternative method is to use high swirl combustion chambers that promote combustion. For the emissions challenge, most automobile manufacturers are working to develop "lean NO_x catalysts," and, as discussed below, both Toyota and Mitsubishi have sold vehicles that combine lean operation and new NO_x catalyst technology since the early 1990s in Japan.

Low cost lean-burn systems that do not need "direct injection" of fuel into the cylinder head can provide up to a 10% benefit in fuel economy by utilizing advanced cylinder head designs and lean air-fuel sensors.

5.2.7 Advanced Tires

Rolling resistance accounts for approximately a third of the loads on an automobile during the EPA test procedure. The magnitude of this resistance is approximately linearly related to the rolling resistance coefficient of the vehicle's tires, so reducing this coefficient through changes in tread design, tire materials, and tire structure will have a significant positive impact on fuel economy.

Tire design and materials have improved steadily throughout the years, with the switch to radials from bias-ply tires beginning in the late 1970s, then the shift to second generation radials beginning in the mid-1980s each achieving about a 20-25% reduction in rolling resistance and a 3-4% improvement in fuel economy.

Additional improvements have recently been introduced by Michelin and other companies and are beginning to penetrate the fleet. Use of these and other, further-improved designs can yield about a 25% reduction in rolling resistance by 2005, with 5% improvement in fuel economy resulting; an additional 3% fuel economy improvement may be possible by 2015 (Hattori et al., 1990). Some of these gains are likely to be offset by manufacturer design decisions that increase tire traction and durability, so that only about half the potential fuel economy gains are likely to be realized. The NEMS model has the improvements occurring in four discrete steps over time to achieve a total 4% benefit in fuel economy.

Aside from these proven technologies, there are a few additional technologies that are not expected to enter the fleet in commercially significant amounts before 2010 under the business-as-usual case assumptions, but that have the potential to impact fleet fuel economy in this time frame if there are appropriate incentives. These are:

Advanced drag reduction (to a C_d of 0.22 for mid-sized vehicles),

Hybrid-electric power trains,

Direct injection stratified charge (DISC) gasoline engines,

Direct injection (DI) diesel engines, and

Proton exchange membrane (PEM) fuel cell power trains.

All but the PEM fuel cell power trains are considered likely to be introduced into the U.S. in small numbers before 2010 (e.g., in limited edition or luxury models). In fact, Volkswagen has already introduced DI diesel engines into the U.S. market as options in its Passat, Jetta, and Golf models. DI diesels cannot meet current NO_x standards for gasoline-fueled automobiles. At this time, diesels have an exemption to U.S. rules on NO_x emissions; however, this exemption is unlikely to stand if large numbers of diesels are sold in the U.S. market. Similarly, DISC engines have been introduced into the Japanese fleet by Toyota and Mitsubishi, but their high cost and U.S. emissions requirements should keep them out of the U.S. fleet for the immediate future – except

perhaps in very limited numbers. As discussed below, however, these technologies could make an impact on U.S. fleet fuel economy before 2010 either in the efficiency scenario, which postulates both increased R&D spending and increased market or regulatory incentives for fuel economy, or in our high-efficiency/low-carbon scenario that postulates better-than-expected luck in technology development.

5.2.8 Advanced Drag Reduction

In our view, significant market pressure on fuel economy could reduce C_d values a bit further than projected by the auto makers. Some existing vehicle designs that have attained lower C_d s without some of the design compromises of the prototypes noted above indicate that a C_d of 0.22 should be practical for a mid-size car without requiring wheel skirts or a sharply tapered rear end.³ This value has been adopted as successfully entering the mass market automobile fleet in both the efficiency and high-efficiency/low-carbon scenarios, and is modeled as an additional 10% reduction in drag over the lowest C_d value in NEMS of 0.245.

5.2.9 Hybrid-Electric Power Trains

Hybrid-electric power trains combine two energy sources with an electric drivetrain, with one or both sources providing electricity to the electric motor. Although many configurations are possible, all have some form of energy storage (battery, flywheel, ultracapacitor, etc.). Hybrids offer a theoretical efficiency advantage over conventional internal combustion engine (ICE) drivetrains for the following reasons:

They offer the potential to recapture some of the vehicle's potential energy that is normally lost (as heat) when the vehicle is braked. In a hybrid, the electric drive motor can be operated in generator mode to brake the vehicle; the electric energy produced is stored in the battery or other storage device.

The hybrid drivetrain allows the vehicle powerplant to be smaller and to operate more efficiently than the powerplant in a conventional drivetrain. In a conventional drivetrain, the engine is sized for the maximum load (usually short-term rapid acceleration) and can produce many times the power it uses during the great majority of its operation. For example, during idle, low speed cruise, or deceleration, the powerplant may be operating below 10% of its maximum power capability, and most engines (especially gasoline engines) are very inefficient at such lower power levels. Because the storage device can absorb any excess power (over that needed to operate the vehicle) produced by the engine, the engine can continue to operate at an efficient power level even when the vehicle loads are low. Also, in a hybrid, the storage device can provide part of the power for maximum acceleration, allowing the hybrid powerplant to be sized for average power requirements or for power requirements in operations where the battery can't help (e.g., during sustained hill-climbing), which are generally lower than acceleration loads – so the hybrid's engine can be smaller.

The net energy gains from the regenerative braking, smaller and lighter powerplant, and improved powerplant cycle efficiency are counteracted by losses in the electrical components (storage device, generator, motor/controller) and their added weight (in particular, weight of the storage device and electric motor). The wide variety of hybrid configurations and component designs, the relatively early stage of development of hybrid powertrain systems, and the ongoing redesign of hybrid powertrain components to satisfy the unique requirements of hybrid operation has yielded a wide range of estimates of the potential efficiency benefits of shifting to hybrid drivetrains. Further, ongoing changes in engine design for conventional drivetrains shift the relative value of hybridization, with reduction in pumping losses achieved by variable valve control, for example, reducing the benefit of hybridization because these are the same losses hybridization is designed to counter. The OTA has estimated that a battery/ICE hybrid can achieve about a 25-35% gain over a conventional drive vehicle with the same type of powerplant, assuming what it considered optimistic values for the efficiencies of the battery and electric motor (U.S. Congress, OTA, 1995). Current examples of operating hybrids that satisfy normal vehicle safety and performances requirements⁴ have not achieved efficiency improvements this high (U.S. Congress, OTA, 1995). On the other hand, the Department of Energy's (DOE's) goal for its hybrid drivetrain R&D program is a doubling of fuel economy, and theoretical analyses of hybrid configurations using simulation models have projected gains ranging as high as the DOE goal (Burke, 1995;

Ross, 1996). In our view, gains this high are unlikely without sacrificing some aspects of performance or operational flexibility. On the other hand, there are active R&D efforts on hybrid components such as ultracapacitors and high-efficiency electric motors that, if successful, could raise the efficiency advantage of hybridization to somewhat higher levels than OTA projects. The efficiency case conforms approximately to the OTA projections; the high-efficiency/low-carbon case assumes exceptional success at improving drivetrain components and reducing costs. This translates to a 28% fuel economy benefit over a 1995 conventional gasoline-fueled car, and a 10% benefit over a DI diesel vehicle for the efficiency case; in the high-efficiency/low-carbon case, the assumed gains are 43% and 23%, respectively.

The primary barriers to successful commercialization of hybrid-electric vehicles are the current high costs of electric motors, controllers, and batteries, and the need for additional progress in reducing the specific power and increasing the efficiency of these electrical components. In particular, there is an urgent need for reliable high-efficiency, high specific power batteries. There recently has been progress on such batteries, but considerable work remains. In addition, there are relatively few suitable engines in the right size category (one liter or so) for hybrids, since automotive engines typically are sized to meet the higher power requirements of conventional drivetrains.

5.2.10 Direct Injection Stratified Charge (DISC) Gasoline Engines

Conventional spark ignition (gasoline) engines are inefficient at part load in large part because they reduce power by throttling back on their air supply, creating large drag losses (so-called "pumping losses") in the stream of intake air. Direct injection stratified charge engines do not throttle intake air; instead, they reduce only fuel flow at part load, operating at fuel/air ratios as low as 1:50. They manage this by injecting fuel directly into each cylinder at high pressures (700 psi or higher compared to 50 psi in a conventional fuel injection system (Markus, 1997)) in such a way that the fuel/air mixture is stratified (thus, "stratified charge"), with high fuel concentrations near the spark plug so as to maintain stable combustion. The combination of zero throttling losses, low fuel use at light loads because of the very lean fuel mixture, and some added benefits of direct injection – particularly, more precise control of combustion and fewer problems such as fuel condensation on intake-port walls – yields substantial fuel efficiency improvements rivaling those of DI diesels.

Concerns with DISC engines include problems with increased NO_x emissions because normal reduction catalysts will not operate in the oxygen-rich exhaust environment of a lean-burn engine; the expense and durability of the fuel injectors, which have to operate at very high pressures ranging up to 2000 psi; and the need for extremely precise control of combustion to maintain smooth performance from the engine as it shifts back and forth between lean to stoichiometric operation.

Both Toyota and Mitsubishi have introduced DISC engines into their fleets in Japan, Mitsubishi with a 1.8 liter, 148 hp engine in its Galant sedan and Legnum wagon, Toyota with a 2.0 liter, 143 hp engine in its Carina sedan (Markus, 1997). Both companies use catalysts to reduce NO_x emissions: Mitsubishi's is a true lean-NO_x catalyst that reacts hydrocarbons with NO_x to form nitrogen, oxygen, water, and carbon dioxide; Toyota's system stores NO_x and reduces it to nitrogen during high power operation when the engine uses a stoichiometric (no excess air) air/fuel mixture (Markus, 1997). Neither system is believed ready to meet U.S. emissions requirements, especially for catalyst longevity. The Toyota system would likely experience difficulties with high levels of sulfur in U.S. fuels, which can poison the catalyst material.

Available data suggest that Toyota's DISC engine provides a 25% fuel economy benefit in the Japanese 10-mode cycle, which could translate to an 18% benefit in the U.S. FTP if emissions problems are solved. This benefit has been used in the efficiency case; in the high-efficiency/low-carbon case, a benefit of 23% is assumed.

5.2.11 Turbocharged Direct Injection (TDI) Diesel Engines⁵

Until recently, all diesel powertrains used in light-duty vehicles in the United States were indirect injection diesels (IDI). In an IDI diesel, fuel is sprayed into a prechamber, mixed with air, and partially burned before the charge is passed into a main combustion chamber where the combustion continues. This design was desirable for automobiles because it yields smoother combustion with less noise and lower NO_x emissions than direct injection designs. These advantages are purchased at the expense of some efficiency losses from heat transfer from the prechamber and pressure losses as the partially burned gases flow through the passages between the prechamber and main combustion chamber.

Advances in fuel injection technology and combustion chamber design, coupled with turbocharging and intercooling, have allowed direct injection diesels to attain smoothness and noise levels comparable to IDI diesels with low NO_x emissions and high specific power (power/weight) levels, approaching that of naturally aspirated 4-valve per cylinder gasoline engines. The best 4-valve turbocharged DI diesels can attain fuel economy improvements of 40% or more over current 2-valve per cylinder engines, though conversion to gasoline equivalent fuel economy yields closer to a 30% gain (diesel fuel is a more energy-dense fuel than gasoline). The 40% value has been used in our analysis, but it assumes that lean-NO_x catalysts will be successfully adapted to diesels to meet NO_x standards. Catalyst researchers generally are considerably less optimistic about success for diesels than they are for gasoline-fueled vehicles.

As noted above, Volkswagen has introduced DI diesels into the U.S. fleet in its Golf, Jetta, and Passat models. These engines are 1.9 liter and produce 105 horsepower. Audi produces a larger 2.5 liter engine for its European models.

5.2.12 Proton Exchange Membrane (PEM) Fuel Cell Powertrains

Fuel cells are electrochemical devices that convert the chemical energy in fuels to electrical energy directly, without combustion. This process avoids the thermodynamic limitations imposed by the Carnot cycle, and fuel cells theoretically can have efficiencies of 90% or greater. With hydrogen as a fuel, fuel cells have emissions only of water; with fuels such as methanol or hydrocarbons, reforming to obtain hydrogen will produce small quantities of carbon monoxide and other pollutants as byproducts and larger quantities of carbon dioxide.

For the immediate future, PEM fuel cells appear to be the clear choice among alternative fuel cell technologies for light-duty vehicle applications because they operate at moderate temperatures (20-120 degrees C) and developers have been able to rapidly improve their power density (from .085 kW/liter in 1989 to about 1 kW/L today) and decrease their costs (platinum loadings, a major cost factor, have been reduced from about 4 mg/cm² in 1990 to current levels of about 0.15 mg/cm²) (Oei, 1997).

Despite rapid progress, fuel cells must overcome major hurdles before they can succeed commercially in the light-duty market. Costs must be sharply reduced. Even with mass production, PEM fuel cells would cost at least \$200/kW to manufacture with today's production technology and cell designs – nearly ten times the cost of ICE engines (Oei, 1997), disregarding the additional cost of needed hydrogen storage or reformers.⁷

Key needs are development of low-cost membranes, size and cost reduction of hydrogen reformers or onboard storage, and improvement of "balance of plant." Also, there are several "engineering" issues that will have to be dealt with once stack design has gotten to the point where serious vehicle design is contemplated – for example, cooling (the low temperature operation of fuel cells means that the heat being rejected is very low grade heat, requiring lots of air movement or large radiator surface areas, neither very appealing to vehicle designers (Borroni-Bird, 1997)) and prevention of freezing in cold weather.

On-board fuel storage represents a significant barrier because hydrogen's energy density is very low,⁸ and the easiest fuel to reform into hydrogen onboard the vehicle, methanol, has no significant supply infrastructure.

Chrysler in partnership with DOE recently announced significant progress towards onboard production of hydrogen from gasoline, which would solve the supply infrastructure problem and allow much easier fuel storage than hydrogen. Not surprisingly, however, the selection of gasoline as the preferred “hydrogen carrier” for fuel cells is by no means an easy call. For example, gasoline’s availability and easier fuel storage must be traded off against the cost and space occupied by the reformer (Jost, 1997).⁹ Toyota has claimed a substantial improvement in hydrogen storage technology using an advanced metal hydride adsorbent that matches the energy density of liquefied hydrogen storage with only 10 atmospheres of pressure required (Yamaguchi, 1997). Presumably, however, this type of storage would be extremely heavy. Other options being pursued by various researchers include direct methanol fuel cells, which preclude the need for a reformer, and the use of ethanol in place of methanol or gasoline as a hydrogen source. The latter option is especially attractive if the ethanol can be produced from cellulosic materials, because the effect on reducing greenhouse gas emissions is particularly large for this technology.

We expect the rate of progress and probability of commercialization of fuel cell powertrains to be sensitive to the level of R&D funding and market pressures to improve overall vehicle fuel economy. Progress has in fact been rapid, as shown by the improvements in power density discussed above. Ford, GM, and Chrysler are all pursuing fuel cell vehicle R&D, as are Japanese and European companies, with Toyota’s and Mercedes Benz’s programs being the most visible. A Canadian company, Ballard, appears to be in a leading position in PEM fuel cell R&D, and has supplied systems to most of the vehicle R&D programs. Given current funding levels and the market’s lack of pressure on fuel economy levels as well as the large amount of development work that remains to be done, however, introduction of fuel cells into mass market vehicles appears likely to be beyond the 2010 time frame, and the base scenario adheres to this projection. This, in fact, was the conclusion of the NRC’s advisory panel overseeing the PNGV program (NRC, 1997, Table H-1). On the other hand, increased funding and market pressure and/or particularly fortuitous progress in the ongoing R&D program might move the date of introduction forward. Further, the newness of the technology and the dependence of the basic fuel cell stack costs on manufacturing design leaves open the potential that the eventual cost of the fuel cell system might be somewhat lower than competing ICE drivetrains; this depends on substantial cost reduction over a range of technologies, because the costs of hydrogen storage or reforming, the electric motor, and even the battery that is likely to be necessary for startup power, all play a significant role in total system costs.

The efficiency case assumes that fuel cells will not be introduced in mass market vehicles before 2010; we note that the major auto makers are not projecting a pre-2010 commercial introduction of fuel cell vehicles even assuming a high level of success in their development programs. The PNGV program envisions that the earliest fuel cells will use a reformer to produce hydrogen from gasoline. We assume that fuel cells in conjunction with a gasoline reformer will be about 70% more efficient than current gasoline engines, but only slightly more efficient than a diesel hybrid drivetrain. The high-efficiency/low-carbon case assumes introduction of commercial gasoline fuel cell vehicles by 2007. Although ethanol from cellulosic material would make an excellent fuel for the fuel cell hybrid and would result in further reductions in greenhouse emissions, we assume the first fuel cell vehicles will use widely-available gasoline.

5.2.13 Fuel Cells in Heavy Trucks and Locomotives

In many ways, fuel cell propulsion may be attractive for large transportation vehicles, such as locomotives or ships, before it is ready for use in light-duty vehicles. Use of fuel cells in heavy trucks will require a breakthrough in hydrogen production, distribution, or on-board storage, or else a breakthrough in reforming technology before it will be competitive with the diesel engine. The drive-cycle thermal efficiency of current heavy-duty diesel truck drivetrains is in the range of 35% to 40%. The drive-cycle thermal efficiency of current methanol steam-reforming fuel cell drivetrains (including electric motor/controller and battery) is also 35% to 40%. Thus, there is likely to be little incentive for heavy trucks to switch to fuel cells until hydrogen fuel cells, with drivetrain efficiencies in the range of 45% to 50%, become available.

Fuel cells may succeed in the locomotive market first because, (1) fuel costs are more important to rail carriers than to truckers, (2) locomotives already use electric traction drive and, (3) fuel cells of the size necessary for locomotive powerplant output (4000 HP) are already commercially viable in stationary powerplant applications.

Therefore, we consider the use of fuel cells in locomotives in the high-efficiency/low-carbon scenario. Fuel cells may also have applicability to marine vessels, again because of their size. We do not introduce marine fuel cell applications in the high-efficiency/low-carbon technology scenario, simply because we are not aware of suitable applicability studies. We believe that analysis of the potential for fuel cell technology in heavier transportation vehicles would likely reveal additional promising applications. Thus, the locomotive fuel cell analysis is intended more to be indicative of potential large-scale fuel cell applications in transportation than a reflection of our judgment of the true potential market.

Locomotives can be broadly classified into two types: local service and line haul. Local service locomotives are primarily older line-haul locomotives that are low powered (2000-3000 HP), and are typically utilized in light load applications. Local service locomotives consume about 120,000 gallons/year of fuel per locomotive. Line-haul locomotives are more powerful (4000 HP) and consume 375,000 gallons/yr of fuel per locomotive. Both types spend considerable amounts of time at idle, over 70% of the time for local service locomotives and over 50% of the time for line-haul. Idle fuel consumption accounts for 38% of fuel consumed in local service locomotives, and only 6.3% of fuel consumed for line-haul locomotives (CARB, 1991; CARB, 1992).

Locomotives have very long useful lives and the engines are rebuilt several times. The diesel engine alone costs about \$400,000, but a complete rebuild costs only about \$100,000 to \$150,000. Engines are typically rebuilt every eight years, and the entire locomotive is rebuilt every 24 years and/or moved to local service at that point. Hence, a useful life calculation of 24 years may be reasonable in terms of a replacement cycle.

A fuel cell based locomotive could utilize methanol, ethanol, or liquefied natural gas (LNG) and could be of the PEM type being considered for cars or the Phosphoric Acid type used for power generation. It is believed that for high power applications, the Phosphoric Acid Fuel Cell is in a relatively greater state of maturity. Several large units are currently operating as prototypes for power generation. Estimates of future fuel cell costs are highly uncertain, but megawatt size Phosphoric Acid units could be manufactured at low volumes for approximately \$1000/kW in the near future, and perhaps at \$400-500 per kilowatt in ten years. At this cost, a typical locomotive unit of 3000 kW would cost \$1.2 to \$1.5 million in 2007 reflecting a cost premium of \$800,000 to \$1.1 million over a diesel engine powered locomotive. It is also possible that "rebuilt" would not be required every eight years so that net cost differences may be smaller over the lifetime of the locomotive. Also, developers of PEM cells for highway vehicles are aiming at sharply lower costs, in the range of \$50 per kilowatt (for the fuel cell only) or lower; although the size, duty cycle, and manufacturing volume of locomotive and automotive power plants are clearly very different, presumably a portion of any cost reductions achieved in automotive fuel cells would be applicable to fuel cells designed for locomotives.

The average efficiency of the fuel cell over the duty cycle would be 1.6 to 1.7 times as high as the diesel engine (whose cycle average efficiency excluding idle is about 35%). Fuel savings of 40% are possible, which is approximately 150,000 gallons/year for a line-haul locomotive. Hence fuel savings alone could pay for the capital cost increases over about eight years, making the technology reasonably cost-effective in the context of a 24-year useful life. Of course, major uncertainties exist in the actual cost of the fuel cell for a 3000 kW unit, the life of the fuel cell, and the maintenance requirements relative to a diesel engine.

If successful, fuel cell locomotives could have a 5 to 6% market share by 2010, and 16 to 18% by 2015, for the total fleet. In the high-efficiency/low-carbon scenario, we assume a 5% share in 2010 and 20% by 2015. We further assume use of cellulosic ethanol, although methanol and LNG would also be likely candidates.

5.2.14 Costs and Timing of Technology

As part of the OTA study, the cost of all the above-described automotive technologies was derived on the basis of near-term estimates, though at high production volume. One possible area for improvement in costs is the effect of research and additional learning to provide an "experience" based cost reduction. Lipman and Sperling (1997) have analyzed cost reductions based on cumulative total production, and concluded that many new technologies experience a 20 to 35% cost reduction for every order of magnitude increase in cumulative

production (i.e., the cost decline function is linear with respect to the logarithm of cumulative units produced). If these new technologies are manufactured at typical automotive volumes from their introduction, then an order of magnitude increase in cumulative production will occur over a span of five to seven years with sales growth over the period. The next order of magnitude increase in cumulative production will take much longer unless the technology essentially increases market share to 100% over the next decade. We have utilized the data from the Lipman and Sperling paper to conclude that a 30% cost reduction over the 1997-2005 period is possible relative to the costs derived for OTA.

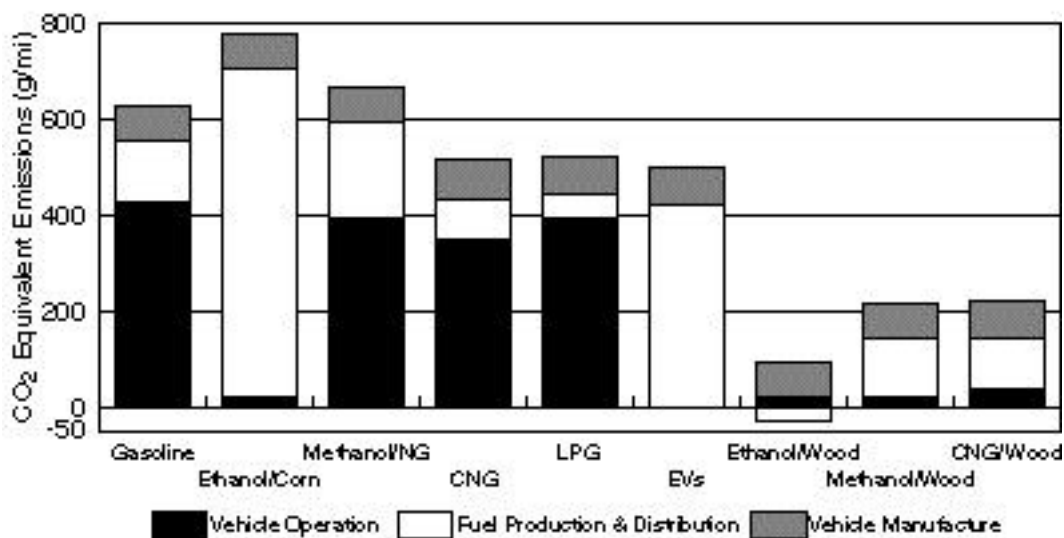
A second factor is the timing of technology introduction. The contrast here is between new technology introduction in a business-as-usual scenario relative to one where both business and government invest in research and development at rates consistent with an accelerated PNGV, coupled with changes in market preferences for fuel economy driven also by changes in government policy (e.g., new fuel economy standards, high motor fuel taxes, etc.). The resulting reduction in lead time is assumed to be 30% relative to the earliest introduction dates forecast by OTA, starting from 1997. In other words, a technology forecast by OTA to be commercialized in 2010 (13 years from 1997) would be expected to arrive in 2006 ($1996 + [13 \times 0.7]$) under the regime of increased R&D spending and market changes. This factor has been incorporated for all post-2005 technologies defined in NEMS or added to the NEMS technology list for the efficiency and high-efficiency/low-carbon cases.

5.2.15 Alternative Transportation Fuels

Alternative Fuels derived from fossil energy sources have limited potential to reduce greenhouse gas emissions. The full fuel cycle greenhouse gas emissions of fossil fuels have been compared in detail by Delucchi (1991, Tables 9a-e), Wang (1996) and others. Several fossil fuel alternatives have somewhat lower CO₂ emissions than conventional or reformulated gasoline (RFG), most notably liquefied petroleum gases and natural gas, whether compressed (CNG) or liquefied (LNG). On the basis of emissions of CO₂ equivalent greenhouse gases per vehicle mile, CNG and LPG offer moderate reductions both for light (Figure 5.1) and heavy-duty (Figure 5.2) vehicles. Methanol from natural gas, while it is a relatively attractive alternative fuel for spark-ignited internal combustion engines, seems to offer no CO₂ reduction potential.

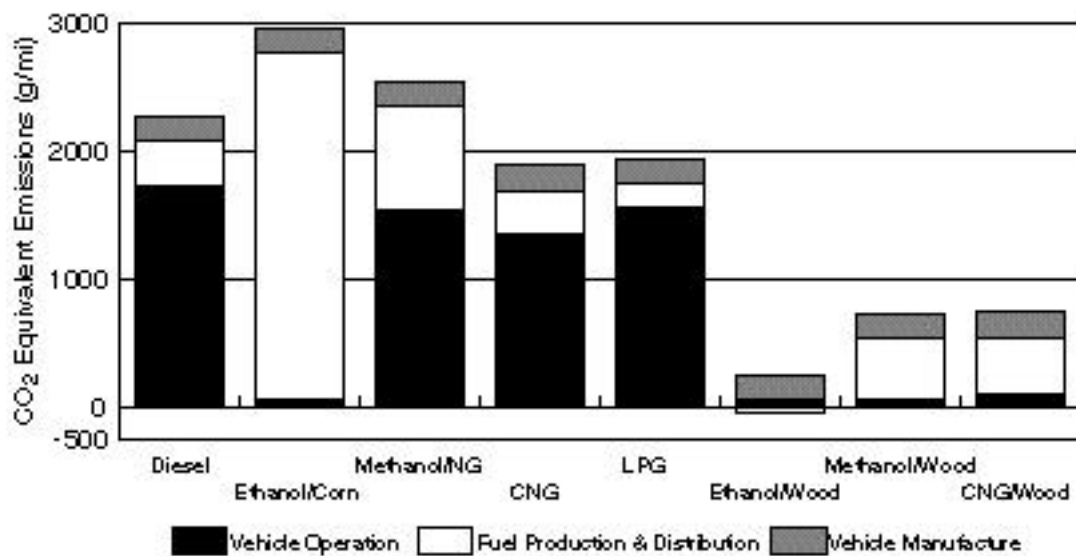
Battery-powered electric vehicles (EVs) can also lower greenhouse gas emissions, depending on the energy source used to produce the electricity stored in the vehicle's batteries. Electricity obtained from nuclear or solar power would very nearly eliminate greenhouse gas emissions. Use of nuclear power is unlikely, however, since nuclear power plants tend to operate at capacity at present and are not likely to supply a marginal increase in demand due to electric vehicle use. Electricity from current natural gas-fired plants would achieve roughly a one-third reduction, and electricity from advanced combined cycle natural gas generations could do even better. Estimating CO₂ emissions reductions from electric vehicles is highly dependent on assumptions about when vehicles will be recharged and how utilities will choose to operate different kinds of generating units. One such set of estimates, developed based on technologies and generation mixes projected for 2015, is shown in Figure 5.3. There are no CO₂ emissions from vehicle operation and emissions from vehicle manufacture are the same for all regions. Largely due to greater use of natural gas in advanced generating units, the south central and west regions are expected to produce the lowest greenhouse gas emissions for EVs operated there.

Figure 5.1 Fuel Cycle Greenhouse Gas Emissions for Light-Duty Vehicles



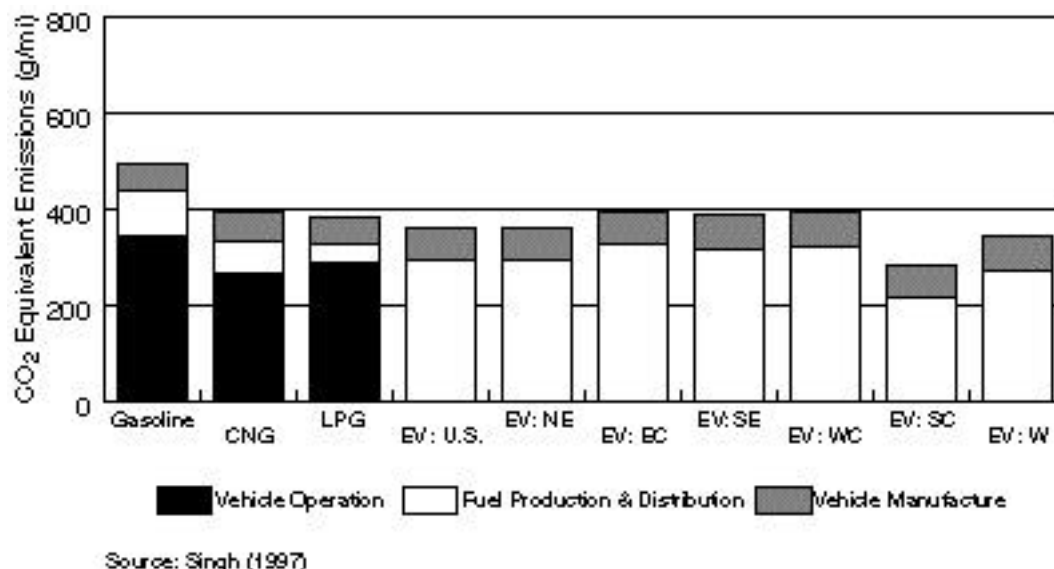
Source: Leiby et al., 1996, Table D-4

Figure 5.2 Fuel Cycle Greenhouse Gas Emissions for Heavy-Duty Vehicles



Source: Leiby et al., 1996, Table D-4

Figure 5.3 Projected Fuel Cycle Greenhouse Gas Emissions of Battery-Powered Electric Vehicles by Region in 2015



The analyses in Chapters 6 and 7 indicate that there is considerable opportunity to reduce carbon emissions in the electric utility sector. A substantial shift towards lower-carbon electric generating facilities will increase the carbon-reducing benefits of electric vehicles. For example, large shifts away from coal and towards natural gas, especially with combined cycle technology, will tend to push the relatively high EV emissions in regions whose dominant fuel is now coal (Figure 5.3) down towards the lower emissions prevalent in areas with primarily gas-fired electricity (e.g. California).

The AEO97 reference case already projects large increases in the numbers of electric and natural gas vehicles on the road. Primarily as a result of zero emission vehicle (ZEV) regulations in California, AEO97 foresees annual sales of 75,000 battery electric cars and 150,000 battery electric light trucks in 2010. To this is added more than a quarter million hybrid electric vehicles. By 2010, the AEO97 reference case projects nearly 2 million battery-electric and over 2 million hybrid electric light-duty vehicles in operation. Given the recent relaxation of ZEV mandates in California, this projection now seems optimistic. The AEO97 reference case also projects compressed natural gas vehicle sales at 325,000 units in 2010 with a total on-road stock of 2.6 million light-duty vehicles. This is more than thirty times the 82,000 CNG vehicles estimated to be on the road today (EIA, 1996c, Table 1). We retain these alternative fuel vehicles in all three scenarios, but do not expand them.

Among the alternative transportation fuels under consideration, biomass fuels derived from wood appear to have the greatest potential to reduce greenhouse gas emissions. Whereas ethanol derived from corn may actually produce higher levels of CO₂ equivalent emissions than conventional gasoline (depending on the fuel used to power the distillation plant, and other factors), ethanol derived from cellulosic sources (wood, switchgrass, wood wastes, agricultural residues, municipal solid waste), can reduce carbon emissions by about 90% for both light-duty and heavy-duty vehicles (Figures 5.1 and 5.2). Cellulosic ethanol has the potential to be more effective than compressed synthetic natural gas derived from wood, partly because of the energy that must be used to compress methane for storage on board the vehicle, and partly because cellulosic ethanol production yields by-products that can be used to generate more electricity than is required to produce the ethanol (Delucchi, 1991, Table 9b; Wang, 1996).

Both battery electric vehicles and compressed natural gas vehicles, but especially battery-powered vehicles, are likely to cost more than conventional gasoline vehicles, will require more frequent refueling, and will have

reduced range (Greene, 1994). It does not appear likely that most consumers will consider these drawbacks to be outweighed by the likely lower fuel costs for these vehicles. Thus, we expect these potential low CO₂ fuel technologies will not easily achieve the business-as-usual forecast market shares (of course, technological breakthroughs in batteries or gaseous fuel storage could make these vehicle technologies much more attractive). It is for these reasons that we focus below on the use of cellulosic ethanol as a transport fuel.

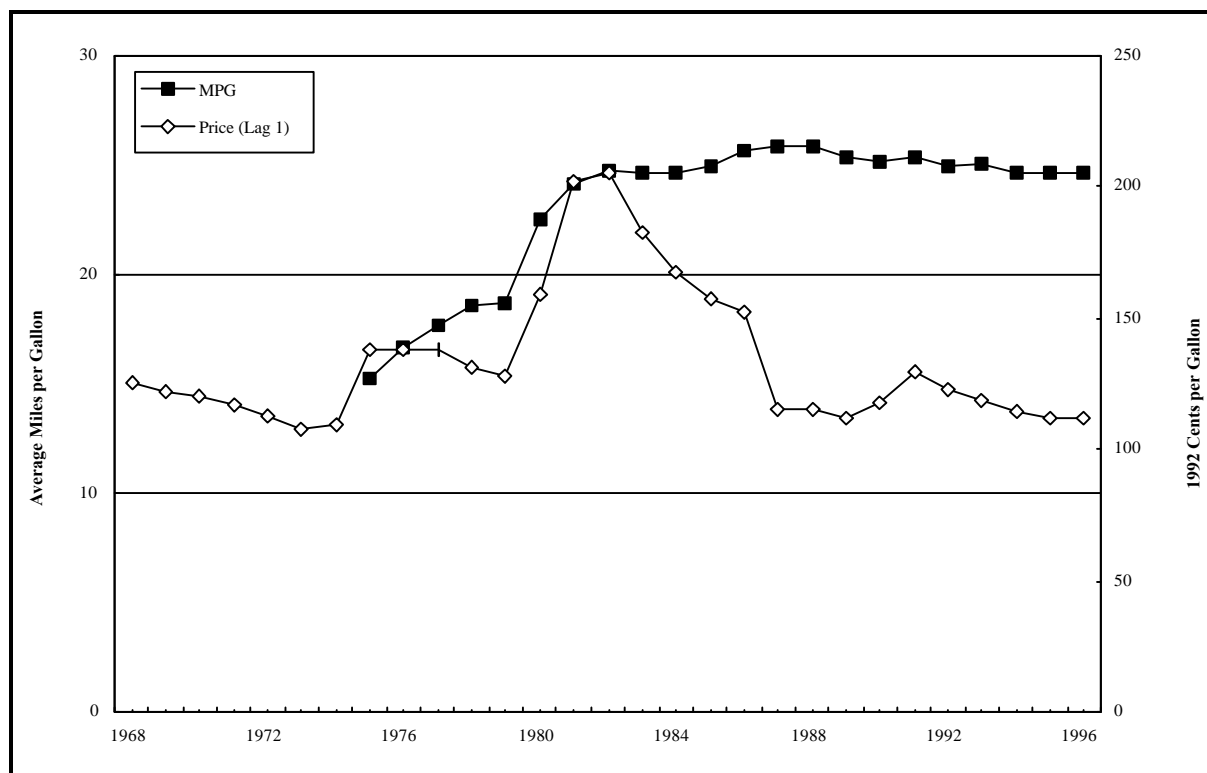
5.3 SCENARIOS FOR 2010

5.3.1 The Business-as-Usual Scenario for Transportation

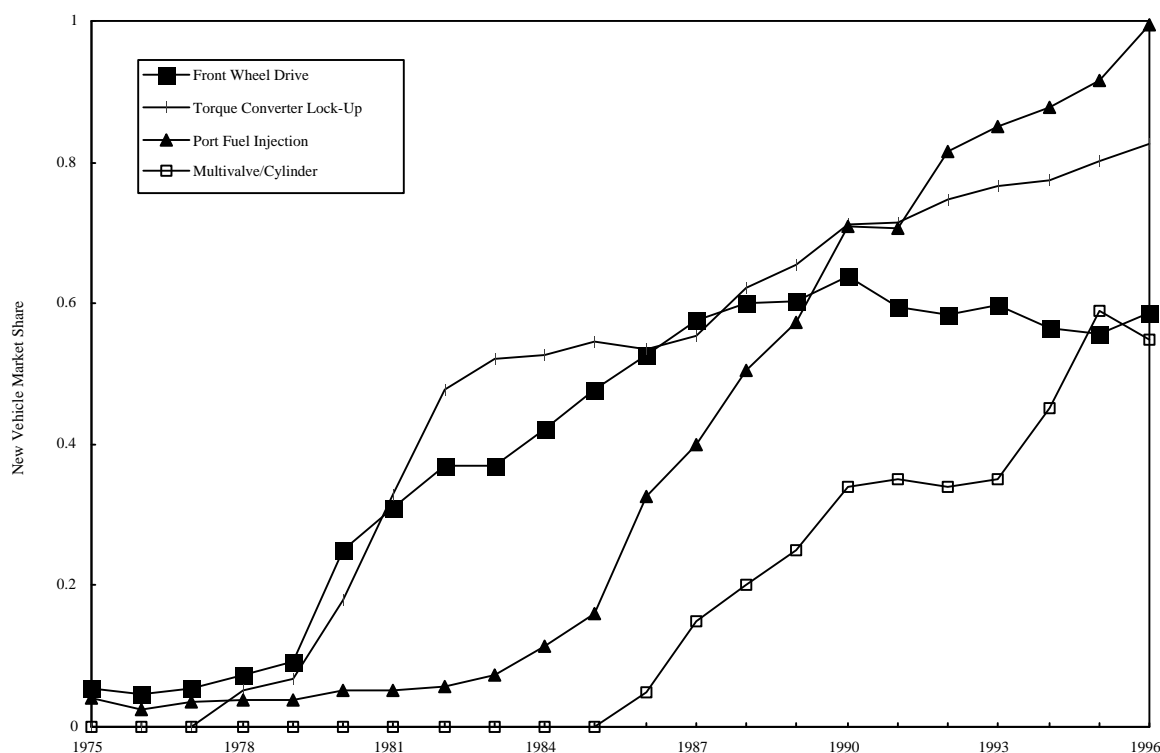
The AEO97 reference case serves as the business-as-usual case, except for its forecast of increasing light-duty vehicle MPG through 2015. The EIA AEO97 reference case projects an increase in passenger car MPG from 27.5 in 1997 to 31.5 in 2010 and 32.6 in 2015. Light truck MPG is projected to increase from 20.5 to 22.9 MPG in 2010 and 24.2 MPG in 2015. We view this as inconsistent with the historical record, which appears to us to indicate that, without increasing fuel prices or a policy intervention such as fuel economy standards, MPG is not likely to increase. Thus, we incorporate zero MPG improvement after 1997 for light-duty vehicles into our business-as-usual case, reflecting the view that the current level of CAFE standards are and probably will remain a binding constraint on light-duty vehicle fuel economy throughout the business-as-usual forecast.

From 1982 to 1997, light-duty vehicle fuel economy remained essentially constant, as shown in Figure 5.4. Of course, motor fuel prices declined sharply at the beginning of the 1983-1997 period, but are at about the same levels today as they were in 1986, and as they were in the early 1970s prior to the first oil price shock. Given that the AEO97 oil price forecast projects no significant increase in oil or gasoline prices through 2015, it is reasonable to ask why fuel economy should increase. The EIA's view is that advances in motor vehicle technology will permit not only fuel economy but other vehicle attributes such as performance and weight to be increased at lower costs, resulting in greater consumer satisfaction. There is a very small increase in the price of gasoline through 2010, and this together with a slowing of income growth may allow the rate of technological advance to catch up with and pass the effect of consumer demand for larger, more powerful vehicles. Because a significant slate of cost-effective current and future fuel economy technologies are represented in the reference case input data, the model takes advantage of them even though fuel prices do not increase. NEMS would make greater use of the technologies if prices increased significantly, but the model is driven partly by technology availability and partly by changes in economic parameters. To some extent, the fuel economy benefits of these technologies are offset by a predicted increase in demand for performance. Nonetheless, a 5 MPG gain remains.

It is difficult to separate out analytically the impacts of CAFE standards and the effect of the marketplace in pushing fleet fuel economy one way or the other. However, we believe that the most likely explanation for the stagnation of fuel economy levels over the past decade is that the CAFE standards have tended to act as a floor on fuel economy, that without the standards the market level of fuel economy would have been lower than it was. We note that important fuel economy technologies, such as fuel injection, front-wheel drive, lock-up torque conversion, 4-valves per cylinder, overhead cam design, improved aerodynamics, and others, all increased their market penetration over the 1983-1997 period (Figure 5.5). Fuel economy technologies were adopted, yet average fuel economy did not increase. There are two major reasons. First, much of the potential to improve fuel economy was used instead to increase average light-duty vehicle horsepower by 55% and weight by 13% from 1983 to 1996 (Heavenrich and Hellman, 1996, Table 1). The second reason is that the impact of a technology on fuel economy depends on how that technology is implemented. To some extent, the fuel economy benefit of a technology is inherent in it. But to a degree, the benefit also depends on the details of vehicle design, specifically whether the technology is implemented with the purpose of increasing MPG or with some other purpose in mind.

Figure 5.4 New Light-Duty Vehicle Fuel Economy and Gasoline Prices, 1967-1996

If CAFE was in fact a binding constraint during the past decade and remains so today, fleet MPG will not begin to increase significantly until a market equilibrium is reached wherein actual fleet fuel economy becomes equal to the fuel economy level that would be achieved in the absence of CAFE standards. In our view, estimating “free market” fuel economy levels is basically a judgment call. We have assumed that market equilibrium will *not* be reached in the base case, so that fleet fuel economy will remain unchanged. In other words, we assume that, although fuel economy technology will continue to be adopted, it will be used to provide other benefits than fuel economy, particularly increased size and performance. Note that the AEO97 reference case also projects increased performance and size over the forecast period; the difference here is a matter of degree, not one of radically different visions of the most likely future.

Figure 5.5 Use of Fuel Economy Technology In New Light-Duty Vehicles

5.3.2 The Efficiency Scenario For Transportation

The efficiency case was created by making reasonable, incremental assumptions about how a concerted effort to accelerate the development and promote the adoption of low greenhouse gas technologies could reduce emissions by the U.S. transportation sector. In this section, the specific changes made to the business-as-usual case are described in detail.

5.3.2.1 Changes to the Modal Models

The efficiency scenario assumes that the time required for market introduction of advanced technologies can be reduced by 25% through increased emphasis on technology R&D, and that several new technologies will be developed that would otherwise not be available in significant numbers before 2010. For light-duty vehicles, these technologies include the following:

- A direct-injection stratified charge (DISC) gasoline engine,

- A turbocharged direct-injection clean diesel engine (TDI Diesel) that meets current and future emissions standards,

- Advanced drag reduction, materials substitution, and engine friction reduction (Drag VI),

- A gasoline/electric hybrid vehicle (Gasoline Hybrid), and

- A diesel/electric hybrid drive vehicle (Diesel Hybrid).

In fact, the diesel hybrid and the 2-stroke engine were not included in the efficiency scenario in order to reduce the number of new engine technologies introduced. We chose the gasoline over the diesel hybrid because its emissions of conventional pollutants can very likely be reduced to extremely low levels, making it attractive for air quality reasons. In the high-efficiency/low-carbon scenario, both the 2-stroke and the diesel hybrid are included (the 2-stroke is assumed to be applicable only in compact or smaller-sized vehicles). The result is that new powerplant technologies all but entirely replace today's conventional gasoline engine by 2015 in the high efficiency scenario. This seems a very ambitious undertaking and one that would require greater expense and a higher degree of technical success than is consistent with the efficiency scenario.

The efficiency scenario assumes a cost reduction of about one-third over estimates developed by OTA (1995) for the advanced technologies shown in Table 5.2, based on the potential for learning-based cost reductions discussed earlier. Among conventional technologies, the cost of CVTs was reduced from \$250 to \$150 and the cost of VVT was cut in half for passenger cars and left unchanged for light trucks. The cost reductions are intended to reflect the success of an enhanced R&D effort.

In the truck freight sector, several new technologies were brought into the forecast by reducing the fuel price threshold at which they would become attractive to buyers. These include:

The LE-55 diesel engine with a 21% efficiency improvement for heavy trucks,

Reduced empty weight,

The turbo compound diesel engine, and

Advanced drag reduction.

The low-emission, 55% thermal efficiency (LE-55) diesel engine is a research target of the U.S. Department of Energy's Office of Transportation Technologies. Compression ignition (diesel) engines are the most efficient heat engines currently available. Very large units (in stationary or marine applications) achieve thermal efficiencies (work output as a ratio to energy content of fuel) of 50%. The best turbocharged diesel engines for heavy trucks achieve 45% thermal efficiency, versus 24% for gasoline engines. The DOE's Office of Heavy Vehicle Technology has established a goal of 55% thermal efficiency for heavy truck engines as an intermediate target on the way to a long-term goal of 63%. These improvements are to be achieved through a combination of increased peak pressure, insulation of pistons, cylinder walls and heads to reduce heat loss, effective recovery of exhaust heat, friction reduction, and improved turbocharger efficiency (U.S. DOE/OHVT, 1996).

For commercial aircraft, an efficiency improvement of 40% was projected for 2015 for new aircraft, comprised of 25% engine efficiency gains and 15% aerodynamics and materials substitution. Also, load factors were assumed to increase to 70% in accord with industry projections as a result of advanced informational and operational technologies. Finally, railroad freight efficiency per ton-mile was assumed to improve at 2% per year, actually somewhat lower than the 2.8%/yr. rate experienced over the past 20 years.

5.3.2.2 New Technologies

Table 5.2 shows the fuel economy benefits, price impacts, years of introduction, effects on vehicle weight, and effects on vehicle performance of the five new technologies that were added to the AEO97 reference case set. Detailed assumptions underlying the cost of fuel economy improvement estimates shown in Table 5.2 are provided as an appendix to this chapter. In order to meet current and future emissions standards, the DISC and TDI Diesel engines, as well as the two-stroke engine included in the business-as-usual case, will require the development of practical, lean-combustion nitrogen oxide catalysts. Catalyst technology for treatment of exhaust emissions has been advanced significantly over the past few years and, with further research, the prospects for its early commercialization appear to be very good (e.g., Buchholz, 1997; Strehlau et al., 1997).

Achieving equivalent results for diesel exhaust NO_x appears to be more difficult, and commercialization of diesel catalysts is likely to occur several years after introduction of gasoline-engine catalysts (U.S. Congress, OTA, 1995). In addition, the DI Diesel will require advances in fuel and emissions control technology in order to meet likely future particulate standards.

Fuel economy benefits, incremental costs and other changes are calculated with reference to a 1995 technology gasoline vehicle. In the NEMS model, light-duty vehicles are classified into passenger cars vs. light trucks, domestic vs. imported, with six size classes for each category. In each class, the 1995 base vehicle has the average characteristics of cars in its class. For example, half of the passenger cars in 1995 had 4-valve per cylinder engines, but less than 10% of the light trucks did (Heavenrich and Hellman, 1996). Thus, the 1995 base vehicle is credited with half of the fuel economy improvement potential and half of the increased cost of 4-valve technology. One hundred percent of passenger cars and 99% of light trucks had port fuel injection, and so the base year vehicles are given 100% and 99% of the fuel economy benefit and cost of fuel injection technology. Future fuel economy improvements are calculated based on the additional penetration of fuel economy technologies beyond the business-as-usual case. Thus, the ability of further use of port fuel injection to improve fuel economy is negligible, while considerable potential remains for 4-valve technology.

Table 5.2 New Light-Duty Vehicle Technologies Added to the Efficiency and High-Efficiency/Low-Carbon Scenarios⁺

Technology	MPG Benefit (%)* (EFF, HE/LC)	OTA Price Increase	Scenario Price	Introduction Date* (EFF, HE/LC)
DISC	18, 23	\$450	\$300	2000, 2000
Turbo DI Diesel	40, 40	\$1100	\$750	2004, 2004
Hybrid/Gasoline	33, 42	\$3000	\$2000	2005, 2005
Hybrid/Diesel	54, 72	\$3500	\$2300	2005, 2005
Drag VI	12, 12	\$256	\$256	2012, 2012
Gasoline Fuel Cell	–, 84	–	\$800	–, 2007

⁺ For an explanation of the assumptions underlying these estimates please see the appendix to this chapter.

5.3.2.3 Valuing Energy Savings

The NEMS model values the fuel economy savings of advanced technology by computing the expected discounted value of annual fuel savings over a payback period. We used a 7% real discount rate over five years whereas the reference case assumes an 8% real discount rate over a four-year payback period. The issue of discounting fuel savings is discussed in greater detail in Section 5.3.5.

5.3.2.4 Trends in Vehicle Performance

The NEMS model predicts consumer demand for increased performance and then adjusts new car MPG downward to reflect the effect of higher horsepower on fuel economy. The model's predictions are consistent with recent trends in light-duty vehicle performance since the early 1980s. Over this period, new vehicle fuel economy was constrained by the federal Automotive Fuel Economy Standards (CAFE) to levels higher than the market would otherwise have demanded. Gasoline prices fell precipitously, starting in 1983 and reaching pre-1974 levels by 1987 (Figure 5.4). As a result, new technology adopted since the mid-1980s, that could have increased fuel economy, was instead used to hold fuel economy constant while increasing vehicle horsepower and weight. The ratio of horsepower to weight for passenger cars increased by 50% from 1982 to 1996). The NEMS horsepower equations essentially continue this trend of ever-increasing performance.

Continued use of new technology to increase performance without increasing fuel economy is consistent with the continued low motor fuel prices projected in the AEO97 reference case. The reference case foresees gasoline prices rising from \$1.15 in 1995 to \$1.23 in 2010 and falling to \$1.18 per gallon in 2015 (1995\$). Such variations are within the noise of year-to-year fluctuations. For example, the actual average price of gasoline in 1995 was \$1.20 and the average price for 1996 will likely exceed \$1.30 per gallon (EIA, 1997, Table 9.4). With no increase in price and binding fuel economy standards, it is likely that performance and weight will continue to increase and fuel economy will not.

In the efficiency case, the trend toward ever greater horsepower is questionable. In the presence of higher fuel economy standards, voluntary commitments by manufacturers to meet GHG targets, “greener” consumers, externality-based fuel taxes, or some other change in policies or preferences focusing consumers’ and manufacturers’ attention on efficiency, it is likely that performance trends would change. Nonetheless, we retain the NEMS performance projection in the efficiency case, but relax it in the high-efficiency/low-carbon case by permitting only half of the projected increase in horsepower. This results in new vehicle fuel economy levels 1-2 MPG higher in the high-efficiency/low-carbon case than would otherwise be the case.

5.3.2.5 NEMS New Light-Duty Vehicle Fuel Economy Estimates

Transforming the technology of transportation energy use takes time. First, manufacturers must implement a new technology. New designs must be engineered, tested, and certified to meet government standards. Generally, capital equipment will also have to be replaced or retooled. The orderly replacement of long-lived production facilities (engine production lines may last 15 years, or more) is important to holding down the cost of technological change. Second, consumers must become accustomed to the new technology, and the supporting infrastructure of maintenance and repair must be developed. Finally, new technologies must compete with existing technologies and with other new technologies. In general, a single technology will not dominate all possible applications (vehicle types and consumer preferences). For all these reasons, new technologies rarely achieve 100% (or even 10%) market penetration of the new vehicle fleet in the first year of introduction. The NEMS model simulates the gradual evolution of technology market shares toward their eventual equilibrium levels by means of technology adoption curves calibrated to historical rates of adoption.

As a result, the NEMS forecast of average fuel economy for new vehicles will lag behind the full technological potential. This is illustrated in Table 5.3, which lists all of the best technology predicted to be available in 2010 and 2015 in the efficiency scenario, except that the diesel rather than the gasoline hybrid is included. The effects of regulations that are likely to reduce fuel economy are also included, but further increases in performance (horsepower/weight) predicted by the NEMS model are not, i.e., horsepower-to-weight ratios are assumed to remain constant at 1997 levels. (This applies only to Table 5.3 – all scenarios incorporate substantial increases in hp/wt ratios.) The combined effect of all technologies could improve the fuel economy of the average passenger car by 100% to 55 MPG in 2010, and by another 20% to over 60 MPG in 2015. Yet, even in the high-efficiency/low-carbon scenario, these levels are not achieved by the new car fleet in the NEMS forecasts.

Table 5.3 Maximum Technological Fuel Economy Potential Versus NEMS New Car Average Estimates

Technology	2010 Fuel Economy Improvement (%)	2015 Fuel Economy Improvement (%)
Material Substitution IV	9.9	13.2
Drag Reduction V	9.2	12.0
Engine Friction III	5.0	6.5
Tires III	5.0	7.0
ACC II	1.0	1.0
Electric Transmission II	1.5	1.5
Electric Power Steering	1.5	1.5
Air Bags	-1.0	-1.0
Emissions Tier II	-1.0	-1.0
ABS	-0.5	-0.5
Side-Impact	-0.5	-0.5
Roof Crush	-0.3	-0.3
Diesel Hybrid	54.0	60.0
Total % Improvement*	100.0	123.0
1997 MPG 27.5	2010 MPG	2015 MPG
Maximum Use of All Fuel Economy Technology		
Miles per Gallon	55.0	61.3
Percent Improvement	100	123
New Car Salesweighted Average Fuel Economy: Low CO2 Scenario		
Miles per Gallon	37.5	41.4
Percent Improvement	36	51
New Car Salesweighted Average Fuel Economy: Breakthrough Scenario		
Miles per Gallon	43.1	50.2
Percent Improvement	57	83

* Total percent improvement is computed as $[(1 * \frac{54}{100}) + (1 + \frac{30}{100}) - 1] * 100$. Summing rather than multiplying the smaller percentage improvements yields a more conservative estimate.

Clearly, faster rates of fuel economy improvement than predicted in either scenario are achievable, but at added cost. The constraint that fuel economy improvements be approximately cost-effective requires that the changeover of technologies and manufacturing capital occur at approximately normal rates. This causes realized new car MPG levels to lag considerably behind the full technological potential. On the one hand, this implies that considerable additional energy-efficiency improvement can be made beyond 2015. On the other, it implies that markets must be encouraged, through public policy measures, to make continuous improvements if cost-effective reductions in CO₂ emissions are to be realized.

5.3.2.6 Changes to the Heavy Truck Model

In contrast to the business-as-usual case, the efficiency scenario for heavy trucks:

- Advances introduction dates for two fuel economy technologies,

- Introduces one additional technology,

- Expands the applicability of several truck technologies,

- Reduces the "trigger price" at which the technologies are assumed to become cost-effective, and

- Accelerates the rate at which new technologies are assumed to penetrate the new truck market.

The AEO97 reference case assumes that the Turbocompound Diesel Engine and the Advanced LE-55 Heat Engine will not be available through 2015. The efficiency scenario assumes these technologies will be introduced in 2003. Advanced drag reduction, which is also excluded from the reference case for heavy trucks is assumed to have become available in 1997.

The additional technology introduced is reduction in vehicle empty weight through material substitution. Reducing vehicle empty weight by 10% should be possible, with a consequent 3% increase in fuel economy (Roberts and Greene, 1983; Greene, 1996a, Table 5.5). Reduced empty weight is assumed to be applicable to all types of heavy trucks.

The AEO97 reference case assumes that advanced drag reduction, the turbocompound diesel, and the LE-55 heat engine will be applicable only to the heaviest diesel trucks. The efficiency case extends the applicability of these technologies to medium-heavy diesel trucks, as well. However, the fuel economy benefits of advanced drag reduction are cut from 18% to 10% for medium trucks to reflect the fact that they are generally operated at lower speeds.

A key factor governing the use of fuel economy technology in the NEMS Heavy Truck Model is the "trigger price." Until market fuel prices reach the "trigger price" level specified for a technology, the technology will not be introduced. Diesel fuel prices never exceed \$8.70 (1995\$) per million Btu (\$1.21/gal.) in the AEO97 reference case. Trigger prices for all but existing technologies, however, are \$9/MMBtu, or greater in the reference case. The efficiency case assumes that all of the new technology can be made cost-effective at \$8/MMBtu.¹⁰

Other parameters controlling the rate and extent of market penetration for technologies were also changed. One of these is the number of years until 99% of the maximum potential market penetration is achieved. For improved tires and lubricants, electronic engine controls, and electronic transmission controls, a value of 20 years is assumed in the AEO97 reference case. But for advanced drag reduction, turbocompound diesel, and the LE-55 engine, 99 years is the assumed value. For the efficiency case, all were set at 20 years. The AEO97 reference case assumed that the LE-55 engine would have a maximum market potential of 50% for heavy-duty diesels. The efficiency scenario assumes a 100% maximum for heavy diesels, but only 50% for heavy gasoline, LPG, and CNG trucks. Likewise, the maximum market potential for other advanced technologies was increased to 100% for the heavy diesel market, but left at the reference case values for other fuel types. For medium diesel trucks the maximum penetration for new technologies was raised to 90%, but left at the reference case levels for other fuel types. These changes do not imply that any of these technologies will actually reach maximum market penetration over the forecast time period. Table 5.4 summarizes the primary fuel economy technologies for heavy trucks in the efficiency scenario for 2010.

Table 5.4 Key Heavy Truck Fuel Economy Technologies for the Efficiency Scenario in 2010

Technology	Year of Introduction	Trigger Price (1995\$/MMBtu)	Maximum Market Potential (other / diesel)	Fuel Economy Improvement % (medium/heavy)
Improved Tires & Lubes	1994	\$7.75	80% / 100%	10% / 6%
Electronic Engine Controls	1994	\$7.75	70% / 100%	2%
Elec. Transmission Controls	1994	\$7.75	75% / 100%	5% / 2%
Advanced Drag Reduction	2000	\$7.75	25% / 100%	7% / 18%
Turbocompound Diesel	2000	\$7.75	25% / 100%	15% / 17%
LE-55 Heat Engine	2003	\$7.75	50% / 100%	19% / 21%
Reduced Empty Weight	1997	\$7.75	90% / 100%	3%

5.3.2.7 Changes to the Rail Model

The AEO97 reference case scenario assumes an annual rate of reduction in rail freight energy use per ton-mile of 1%. Since 1972, the average annual rate of reduction in energy use per ton-mile has been 2.8% per year. The vast majority of this improvement has been due to operational efficiency improvements reflected in increased load factors per car (Greene and Fan, 1995, p. 15). Higher load factors are partly due to the restructuring of the rail industry following deregulation in 1980, and partly due to the use of advanced technology for managing operations. Technologies such as lighter weight and higher capacity cars, lower resistance axle bearings, rail-wheel lubrication and improved efficiency locomotives also played an important role (Cataldi, 1995). These technologies are, as yet, still only partially implemented. Based on Cataldi (1995), advanced technologies that can play a role in substantially reducing rail energy use in the future include the following:

Flywheels: Trains presently give up large amounts of kinetic energy on downgrades that could be transferred to flywheels and later used to power the train. The volume and mass necessary to store huge quantities of power can be readily accommodated on trains.

Oxygen-enrichment to increase engine thermal efficiency: Membranes that exclude part of the free nitrogen in the air, thereby enriching the oxygen concentration, can be incorporated into locomotives' air filtration systems. This technology should benefit new, higher power density engine designs, while helping to hold down their nitrogen oxide emissions.

Alternative fuels: Railroads and locomotive manufacturers have been studying and testing the use of natural gas fired locomotives. Once again, the ability of trains to accommodate the volume and mass of storage systems for liquefied natural gas gives them a distinct advantage over smaller vehicles in the application of this technology. Although natural gas locomotives are not expected to provide energy-efficiency gains over diesels, natural gas will produce fewer CO₂ and NO_x emissions and reduce U.S. dependence on oil.

Fuel cells: Beyond 2010, fuel cells for locomotives hold promise. Locomotives already use electric drive systems. And carrying fuel, even compressed hydrogen in large volumes, is less of a problem for trains than for highway vehicles.

Because existing energy-efficiency technologies have yet to achieve full utilization, because other promising options exist, and because further operational efficiency gains are likely with the advance of information technology and some additional railroad consolidation, rail energy-efficiency improvements could continue at a substantial rate. A concerted effort to develop and implement cost-effective technologies is represented here by a 2% annual improvement in ton-mile efficiency in the efficiency case compared with the 1% rate assumed in the AEO97 reference case.

5.3.2.8 Changes to the Air Model

No new technologies were introduced in the NEMS Air Travel Model, but several important changes were made to promote and accelerate the introduction of fuel efficient technology in accordance with goals set by the Committee on Aeronautical Technologies, Aeronautics and Space Engineering Board of the NRC. Broadly, these goals call for a reduction in fuel burn per seat of about 40% by the 2010 to 2015 time period, to be achieved through a combination of improved propulsion system performance (25%) and aerodynamic and weight improvements (15%) (NRC, 1992, p. 49).

Once again, in the AEO97 reference case, new technologies do not enter the commercial aircraft market because trigger prices are set well in excess of \$1.00 per gallon and jet fuel prices never exceed \$0.80/gal. over the forecast period. Trigger prices for ultra-high bypass turbo-fans, already in use on the new Boeing 777s, were lowered to \$0.58/gal., just slightly above current jet fuel prices. Advanced aerodynamics, weight reduction through advanced materials use, and improved engine thermodynamics, were all given the same, lower trigger price. The prices of turboprop engines and laminar flow control were left at levels high enough to prohibit their introduction on new aircraft through 2015.

Ultra-high bypass turbofans were introduced in 1995. The other three technologies were assumed to be introduced in 2000. Consistent with estimates presented in NRC (1992), Greene (1992, Table 4), and Greene (1996b), the efficiency improvement potentials for all four new technologies were set at 15%.

Finally, the AEO97 reference case predicts no changes in aircraft load factors. Aircraft industry analyses foresee commercial load factors increasing to 70% by 2015 (Boeing, 1995, p. 25; McDonnell Douglas, 1996, p. 18). The industry view is adopted in the efficiency scenario, on the grounds that it will very likely be advances in information technology that permit the increase in load factors. On the other hand, although the industry predicts an increase in aircraft size (seats/aircraft) of about 15% by 2015 while the AEO97 reference case does not, no such increase is included in the efficiency scenario on the grounds that more seats per aircraft will be less a reflection of technological change than of airframe choice.

5.3.2.9 Introduction of Cellulosic Ethanol

Alternative fuels derived from fossil fuels have limited potential to reduce greenhouse gas emissions. The full fuel cycle greenhouse gas emissions of fossil fuels have been compared in detail by Delucchi (1991, Table 9a), Wang (1996), U.S. DOE (Leiby et al., 1996, Tables D-4 and D-5), and others; see Wang (1996) for a review. Several fuel alternatives have lower CO₂ emissions than conventional or reformulated gasoline (RFG), most notably liquefied petroleum gases (LPG), methane and battery-powered electric vehicles in certain regions, whether compressed (CNG) or liquefied (LNG). Estimates of greenhouse gas emissions are strongly dependent on context and assumptions. Absolute levels and sometimes the relative rankings of fuels vary across studies. Several general patterns seem to hold up, however. For example, fossil-fuel based alternatives to gasoline or diesel fuel, including battery-electric vehicles where substantial amounts of coal are used for electricity generation, offer about a 20% net reduction in greenhouse gas emissions per mile (Figure 5.3).

In the context of this analysis, a 20% reduction in greenhouse gas emissions will not create a strong incentive to adopt an alternative fuel. For light-duty vehicles, if society's willingness to pay for greenhouse gas emissions reductions were on the order of \$25-\$50 per tonne of carbon, this could justify up to a \$0.06 to \$0.12 per gallon subsidy¹¹ for a fuel that produced no greenhouse gas emissions. A 20% reduction would therefore be worth \$0.01 to \$0.02 per gallon, hardly enough to get motorists' attention. Also, the principal near-term alternative fuels entail some increase in vehicle cost or loss of amenity (Leiby et al., 1996). Thus, unless much higher incentives are introduced, it is unlikely that enough substitution of alternative fossil fuels for conventional gasoline will occur to produce significant greenhouse gas reductions in transportation (Leiby et al., 1996).

Alternative fuels produced from renewable biomass feed stocks can yield significant reductions in greenhouse gas emissions. The most recent estimates indicate that ethanol derived from cellulosic feed stocks (as opposed

to grain) produces less than 1% as much greenhouse gas emissions on a fuel cycle basis as conventional gasoline or diesel fuels (Singh, 1997).¹² Table 5.5 shows the greenhouse gas emission coefficients used to estimate the effects of cellulosic ethanol use and increased demand for diesel fuel on transportation sector greenhouse gas emissions. Ethanol from cellulose generates negligible amounts of greenhouse gases in comparison to fossil fuels or ethanol from grain. Whether ethanol is derived from grain or woody biomass, the carbon in the fuel itself does not count because equivalent carbon will be recaptured from the atmosphere by the next rotation of crops. The differences lie in feed stock cultivation, fertilizer manufacture, and fuel production. Corn requires more cultivation and more fertilizer than woody crops, and fertilizer production, in particular, generates significant greenhouse gas emissions. Whereas distillation of alcohol after the fermentation of grain is energy intensive, by-products from the wood-to-alcohol process will produce excess power, on net, resulting in a greenhouse gas credit for replacing fossil fuels with biomass in the generation of electricity. Indeed, given current practice, ethanol from corn may produce more greenhouse gas emissions than gasoline, on a per Btu basis. Thus, ethanol from cellulosic feed stocks will not only reduce greenhouse gas emissions by replacing gasoline, but might achieve even greater benefits by replacing ethanol from corn. However, the net greenhouse gas balance of ethanol production from corn is strongly dependent on future corn yields, the market for distillation byproducts, and the efficiency of and fuel used in distillation (currently, coal is often the preferred fuel because of corn-based ethanol's disadvantage in greenhouse gas emissions, but future widespread use of corn stillage as fuel would swing ethanol's greenhouse gas emissions strongly towards a positive balance).

A new process for producing ethanol from cellulosic biomass that appears to have the potential to dramatically reduce costs is under development by the U.S. DOE's National Renewable Energy Laboratory (Chem Systems, Inc., 1993). After initial preparation of the biomass, pretreatment with sulfuric acid and then steam is used to expose the cellulose and convert xylan to xylose. Two percent of the resulting mixture is separated for conversion to cellulase, an enzyme that hydrolyzes cellulose. The cellulase is then combined with the rest of the mixture fermented in a key step known as simultaneous saccharification and fermentation (SSF) because the hydrolyzation of cellulose and the fermentation of xylose occur simultaneously. The inclusion of xylose fermentation in this step increases the output of ethanol by about 25% over previous processes. Effluent from the SSF process goes to an ethanol purification and solids separation phase, which produces ethanol and solids. After removal of water, the solids are burned as fuel to cogenerate steam and electricity required for the plant, with surplus electricity that can be sold as a byproduct.

Table 5.5 Greenhouse Gas Emissions Factors for Transportation Fuels

Fuel	g/Btu	Btu/gallon	g/gallon
Conventional Gasoline			
Summer	0.10554	114,500	12,084
Winter	0.10304	112,700	11,613
Average	0.10421	113,537	11,832
Diesel	0.09617	128,700	12,377
Ethanol from corn	0.13390	76,100	10,190
Ethanol from cellulose	0.00076	76,100	58

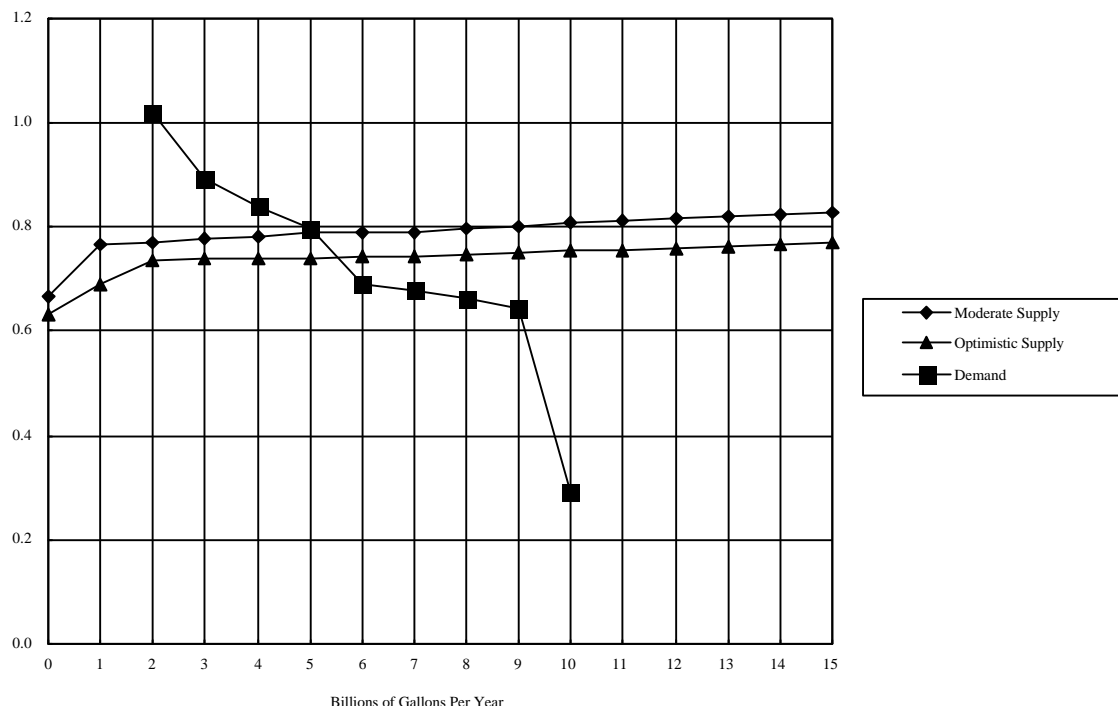
Source: Singh (1997)

Initial estimates of the cost of ethanol produced by the NREL process ranged from \$0.78 to \$1.27 (1990\$) per gallon, plant gate price (Chem Systems, 1993, Tables II-9 to II-13). However, recent cost projections (Bowman et al., 1997) based on a comprehensive assessment of feed stock supply in the United States (Walsh et al., 1997) and anticipated improvements in the ethanol conversion process predict that much lower production costs can be achieved by 2010 or 2015. Ethanol can be produced from a variety of cellulosic feed stocks: short rotation woody crops, switch grass, softwood and hardwood wastes, agricultural residues, and even municipal solid

wastes. Selecting the lowest cost feedstock at each level of output, aggregate ethanol supply curves were constructed for 2000, 2005, 2010, and 2015 under “moderate” and “optimistic” assumptions. The optimistic curves assume that the yield improvements of the moderate case are accelerated by five years, with the net result that the real cost of feed stocks does not rise over time. The moderate scenario curves are used in the efficiency scenario. The optimistic case, being similar in intent to our high-efficiency/low-carbon scenario, is used in that scenario.

In the moderate scenario, ethanol production costs drop dramatically after 2005, the year in which advanced ethanol conversion technology is assumed to be introduced. In 2000, the first billion gallons cost \$1.10 (1995\$) per gallon at the plant gate, which rises to almost \$1.25 per gallon at a 10 billion gallon output level. These prices exclude motor fuel taxes and transportation costs. By comparison, the average refinery price of all grades of gasoline in 1995 was \$0.63 per gallon (EIA, 1996a, Tables 5.20 and 5.21). Because ethanol has only about two-thirds of the energy content of gasoline, the comparable price of ethanol per gasoline energy equivalent gallon would be \$1.63 for the first billion gallons and \$1.85 at the 10 billion gallon level of output. By 2010, the cost of ethanol drops to about \$0.75 per gallon (\$1.11 per gasoline equivalent gallon) at the 1 billion gallon output level, \$0.79/gallon (\$1.17 equivalent) at 10 billion gallons of production. Even in the optimistic case, the first billion gallons cost \$0.67/gallon (\$.99 equivalent), increasing to \$0.73/gallon (\$1.08 equivalent) at the 10 billion gallon output level. Despite dramatic reductions in the cost of producing ethanol from biomass, because of the lower energy content of ethanol, ethanol still cannot compete with gasoline as a pure fuel.

We conclude that the market for cellulosic ethanol in 2010 will be largely as a blending component for gasoline. Demand curves for ethanol for blending with gasoline have been estimated by Hadder (1997) for the year 2010. These show the value to refiners of being able to produce a gasoline refined to be blended with alcohol downstream. Ethanol increases the gasoline's octane rating and adds oxygenates that are required in certain areas under the Clean Air Act. The demand for ethanol as a blending component turns out to be sensitive to the market share of RFG. The more RFG that is required, the lower the demand for ethanol. We assume that RFG's market share remains at its current level of about 30%. Estimated ethanol demand increases as its price declines, from 2 billion gallons per year at an ethanol price of just over \$1 per gallon to 5 billion gallons at \$0.80/gallon and 9 billion at \$0.65/gallon. From this point, increases in demand associated with further price decreases drop off sharply as the limits of economical blending are reached. The moderate 2010 supply curve for cellulosic ethanol intersects the demand curve at about 5 billion gallons per year (Figure 5.6).

Figure 5.6 Biomass Ethanol Supply and Demand for Ethanol in Gasoline Blending

These calculations include no tax subsidy for cellulosic ethanol from biomass. If the projected supply curves are correct, cellulosic ethanol would require no subsidy to be economically attractive as a blending component for gasoline. The current tax subsidy for ethanol – now produced from grain – is due to expire, and the future of the industry is uncertain. Assuming discontinuation of the subsidy, cellulosic ethanol would displace corn-based ethanol from the gasohol, yielding significant greenhouse gas emissions reductions.

5.3.2.10 Adjustment of NEMS Gasoline Forecast

The 5.5 billion gallons of cellulosic ethanol demanded in the efficiency case reduce greenhouse gas emissions by 13 million tonnes of carbon equivalent in 2010 compared to the business-as-usual case. Cellulosic ethanol is assumed to replace first corn-based ethanol, and then conventional gasoline. The Federal Highway Administration (FHWA) estimates that 1.214 billion gallons of ethanol were used in gasohol in 1995 (U.S. DOT/FHWA, 1996, Table MF-33E). If gasohol made from corn-based ethanol were to maintain a constant share of the gasoline market, then corn-based ethanol use would grow to 1,263 million gallons in 2010, then shrink to 1,119 million gallons in 2015. Table 5.6 shows the projected demand for cellulosic ethanol, the corn-based ethanol assumed to be replaced and the impact on fuel cycle greenhouse gas emissions. Because the upstream effects cannot be assumed to be accounted for in the other sectoral models, they are included here. Note that the reduction is shown in tonnes of carbon, while the emissions before and after are in tonnes of CO₂.

Table 5.6 Impact of Cellulosic Ethanol on Greenhouse Gas Emissions from Light-Duty Vehicles in 2010

	Efficiency	Optimistic
Cellulosic Ethanol (million gallons)	5,514	7,480
Corn Ethanol Displaced (million gallons)	1,263	1,119
Gasoline Equivalent Energy Displaced (million gallons)	3,696	5,014
GHG Emissions Before (million tonnes CO ₂ per year)	46.6	62.2
GHG Emissions After (million tonnes CO ₂ per year)	0.3	0.4
GHG Emissions Reduction (million tonnes C per year)	12.6	16.8

5.3.2.11 Adjustments for Increased Light-Duty Vehicle Diesel Use

Because the TDI Diesel engine and the Diesel-hybrid technologies were introduced in the NEMS Transportation Sector Model as fuel economy technologies, the fuel-type accounting algorithms of NEMS were bypassed. We introduced the advanced diesel in this way because we believe that its characteristics will be more similar to gasoline engines than the diesels available in the past. The TDI will fully meet all gasoline vehicle standards and will be quite similar in terms of performance, noise, and odor.¹³ Thus, an adjustment must be made *ex post*, to transfer an appropriate amount of energy from the gasoline to the distillate category. The adjustment affects the energy use projections in three (relatively minor) ways. First, the TDI Diesel's impact is specified in terms of a change in miles per gallon. Since diesel fuel contains more Btu per gallon than gasoline and since the NEMS model assumes that gasoline is being consumed, the energy use transferred from gasoline to diesel must be increased by the ratio of diesel to gasoline Btus per gallon. Second, distillate fuel produces slightly less carbon emissions per Btu than gasoline. Therefore the estimated carbon emissions must be adjusted both for the slight increase in energy use and the slightly lower emissions per Btu for that greater energy use (the net result is a very small increase in carbon emissions). Third, and finally, the reduction in gasoline use reduces the potential pool for ethanol blending in gasoline. As a result, the demand for ethanol must be adjusted downward to reflect the lower level of gasoline use. The net result of all of these changes on energy use and carbon emissions is less than 1%.

5.3.3 The High-Efficiency/Low-Carbon Scenario for Transportation

The high-efficiency/low-carbon scenario postulates the introduction before 2010 of several new technologies and combines them with other changes to reflect greater success in developing and implementing low greenhouse gas technologies and greater public concern over greenhouse gas emissions. Note that successfully achieving these outcomes requires some technological breakthroughs, implying that the outcomes are significantly less certain than those in the efficiency case. As we pointed out in the introduction to this chapter, the high-efficiency/low-carbon scenario is best characterized as an "optimistic" version of the efficiency scenario's "most likely" assumptions. Both must be considered responses to intensified R&D effort and new policy measures to push the market toward low-carbon technologies. A \$50/ton carbon tradable permit price could be one of the necessary policies, but it is not the principal difference between our efficiency and high-efficiency scenarios.

5.3.3.1 Light-Duty Vehicles

Changes for light-duty vehicles include introducing a fuel-cell hybrid in the year 2007 and reintroducing the diesel hybrid and the 2-stroke engine for smaller vehicles. In the projections shown here, we assume that the fuel cell hybrid vehicle uses gasoline which is reformed to provide hydrogen for the fuel cell's operation (e.g., Jost, 1997). The vehicle could just as easily have been designed to operate on alcohol fuels. The gasoline fuel cell hybrid achieves an 84% efficiency gain over a conventional gasoline vehicle, assuming major progress not only in fuel cell and gasoline processor technology, but also in electric motors and other electric drivetrain components. Because a major breakthrough would be required to make this vehicle marketable, we do not

attempt to estimate its cost. Instead, we assume that it will be cost-effective on a life-cycle cost basis – that is, that its incremental cost will be equal to its lifetime fuel savings. This implies a price increment of \$800. Note that this value is not meant to be interpreted as a forecast of likely future fuel cell costs; instead it allows us to evaluate the consequences of such an optimistic outcome.

Some of the technologies necessary to produce an 84% efficiency gain for the fuel cell hybrid would also make the internal combustion engine hybrids, both gasoline and diesel, somewhat more efficient (e.g., ultra high-efficiency electric motors, improved energy storage devices with high specific power and high in/out efficiency). Fuel economy gains for the gasoline and diesel hybrids are boosted to 42% and 72%, respectively. A more optimistic assumption is made for the DISC engine, as well. Its fuel economy benefit is increased to 23% from 18%.

If Intelligent Transportation Systems technologies are highly successful, they should be able to improve traffic flow, resulting in higher on-road fuel economy. To reflect this, the on-road fuel economy factor, which otherwise deteriorates by 3% from 1997 to 2015, is held constant. The high-efficiency/low-carbon case further assumes that the current emphasis on horsepower (HP) will abate substantially, although increased HP will still be valued. This case is consistent with a change in attitudes favoring "greener" automobiles or policies to encourage higher MPG. To reflect greater public concern over greenhouse gas emissions, the demand for increased horsepower is reduced by decreasing its sensitivity to income, from an elasticity of 0.9 to 0.5.

As noted earlier, there are other potential technology breakthroughs capable of significantly reducing greenhouse emissions (e.g. breakthroughs in batteries for electric vehicles, or in gas storage for natural gas vehicles (see box)). These were left out of the high-efficiency/low-carbon scenario not because they are necessarily less plausible than fuel cells, but because the inclusion of large numbers of technology breakthroughs in a single scenario would be implausible.

Other Potential Breakthrough Technologies

Aside from the new technologies postulated in the high-efficiency/low-carbon scenario, other potential technologies could yield substantial reductions in greenhouse gas emissions with technology breakthroughs or, in some cases, with a substantial market push. In the light-duty vehicle market, for example, battery electric vehicles have potential to reduce greenhouse gases if they can greatly increase their market share and improve their energy efficiency. For example, several recent studies have concluded that, under plausible assumptions about EV efficiency and the mix of fuels and technology used to generate recharge electricity, use of EVs will yield net reductions of greenhouse gases. Delucchi (1997) estimates a national average reduction of 26% in 2015, with power generation heavily weighted to coal; whereas Wang (1997) estimates a 19% reduction in 2005. Areas with predominately natural gas-generated electricity could have much larger savings. Note, however, that these results are dominated by assumptions about EV and baseline gasoline vehicle efficiency, type of fuel and technology used for power generation, inclusion or exclusion of non-CO₂ greenhouse gases, and the types of trips replaced by EV use; it is relatively easy to construct plausible scenarios with much higher or lower reductions in greenhouse gases, or even increases (with coal-fired electric power and extremely efficient competing gasoline vehicles).

Crucial technological roadblocks for EV market penetration are:

- Battery improvements – especially higher specific energy and power, lower cost, improved longevity, higher in/out efficiency,
- Power electronics – especially lower cost, and
- Electric motors – especially higher efficiency over a range of driving cycles and higher specific power.

There are claims that transportation use of alternative fuels other than electricity (particularly compressed natural gas) will yield strong greenhouse benefits. In natural gas's case, recent analyses have shown contrasting greenhouse effects. For example, Delucchi (1997) estimates a 20% reduction in greenhouse gases compared to gasoline use in 2015, whereas Wang (1997) estimates a 5% *increase* in 2005. The primary difference in the two analyses is that Wang computes a 10% energy-efficiency penalty associated with switching to CNG, based on recent test data; Delucchi estimates an 11% improvement in energy efficiency based on potential efficiency gains from higher compression CNG engines. Delucchi's optimism may well be the more appropriate approach for the longer term, but at best CNG offers only a modest greenhouse emissions improvement.

Although we selected fuel cell vehicles fueled by gasoline (with onboard fuel processors) as the "breakthrough" technology in the high-efficiency/low-carbon scenario, some analysts believe that the direct use of hydrogen as a fuel is sufficiently more attractive to outweigh the disadvantages of hydrogen's low energy density (complicating onboard storage) and lack of a supply infrastructure (Ogden, 1977). The advantages of direct hydrogen include avoidance of the added weight and cost of the fuel processor and larger fuel cell required (fuel cell performance is reduced because the processor does not produce pure hydrogen), and reduced vehicle efficiency because of the energy losses in the processor and added vehicle weight (assuming the higher fuel storage weight for hydrogen is less than the weight savings from removing the processor and reducing fuel cell size). Although lack of infrastructure still represents a barrier, there have been advances in small scale-steam reforming of natural gas that could greatly ease the introduction of a viable hydrogen supply infrastructure (Ogden, 1977).

5.3.3.2 Changes to the Medium and Heavy Truck Model

Medium heavy trucks are typically operated locally in pick-up and delivery mode. For such vehicles, hybrid technology, with regenerative braking and energy storage capabilities, should offer significant advantages. It is assumed that a diesel hybrid becomes available to heavy trucks starting in the year 2005. This technology is assumed to offer the same 72% fuel economy benefit as the light-duty vehicle version.

Greater success in materials, aerodynamics, tires, and engines, should make these technologies more economically attractive to truckers. Since the NEMS Heavy Truck Model does not explicitly include an economic trade-off between fuel savings and technology penetration, this effect was simulated by shortening the time to 99% penetration for each technology by 30%. For most technologies, this implies a 15 year period from time of introduction to nearly full market penetration.

5.3.3.3 Changes to Other Modes

Several changes were made to the commercial air model inputs. Starting in 2005, propfans were assumed to be available for smaller commercial aircraft. Propfans offer a 20-30% efficiency improvement over high bypass turbofan engines, and 10-15% over even ultra-high bypass engines. Development of propfans has been hindered by concerns about initial cost, maintenance, and vibration. Propfans are made available to only one-third of new aircraft in the high-efficiency/low-carbon scenario. Additionally, partial success in hybrid laminar flow (HLF) technology to reduce drag is assumed by 2010. Although HLF has the potential to reduce fuel use by 15% or more, only a 9% efficiency gain is assumed due to the continuing difficulties in developing a practical system. In the efficiency case, ultra-high bypass engines are assumed to give a 10% efficiency gain, thermodynamic improvements provide a 15% gain, and advanced aerodynamics yield an 18% improvement. In this case, those are increased to 17%, 18% and 27%, respectively, certainly optimistic but not implausible estimates (for example, see Greene, 1992, Table 4).

The annual efficiency improvement rate for railroads is increased to 2.5%, still slightly lower than the 2.8% rate achieved over the past two decades. Waterborne freight's efficiency improvement rate is bumped up to 1% per year from 0.05% to reflect a 10% total efficiency gain achievable through improved hull designs and coatings. In fact, these modes have substantial potential to use alternative power plants and fuels, as reflected in the 2020 technology discussion below.

5.3.4 Comparison of Forecasts

The efficiency and high-efficiency/low-carbon scenarios indicate that advanced energy technologies could reduce emissions of greenhouse gases from transportation by 12-17% by 2010 and by 18-25% by 2015 (Table 5.7). Although these are large changes, they may appear modest compared to the changes in new vehicles, the "leading edge" of changes in the entire transportation fleet. Changing the technology of transportation requires turning over a vast stock of vehicles, and this requires decades. As a result, the impact of advanced technologies introduced between now and 2010 will only just begin to be felt in 2010 and will still not have achieved its full effect by 2015. This phenomenon can be most easily seen by comparing the fuel economy of new cars and light trucks to that of the entire fleet of light-duty vehicles. In the efficiency case in 2015, for example, new cars average 41.4 MPG and light trucks 31.9 MPG (EPA-rated fuel economy), but the fleet as a whole lags behind at 28.2 MPG (24.0 MPG onroad). Given enough time to turn over the stock of vehicles, the eventual light-duty fleet MPG will climb about one-third higher to nearly 38 MPG (32 MPG onroad). The time lag required for new technology to penetrate the light-duty vehicle fleet is a common feature of all modes. Thus, the energy savings and greenhouse gas reductions shown in Tables 5.7 and 5.8 for 2010 and 2015 reflect less than half of the ultimate savings that the technology introduced over this period will eventually achieve.

Passenger car and light truck fuel economy improvements are, in general, attributable to the combined effect of many fuel economy technologies rather than a single, dominant technology. A number of improvements to conventional engines combine to increase average new vehicle MPG in 2010 by almost 20% for passenger cars and by about 10% for light trucks. These include engine friction reduction, greater use of multi-valve engines,

and variable valve timing and lift control. Substitution of lighter weight materials, aerodynamic drag reductions, various transmission improvements, and the combined effects of advanced lubricants, tires, and accessories, each contribute 2-5% gains. Of all the technologies added to the efficiency and high-efficiency scenarios, the lean-burn gasoline engines (DISC and 2-stroke) deliver the greatest fuel economy benefits, about 15% for passenger cars and 12% for light trucks. These numbers represent sales weighted average effects, taking into consideration the fact that even in 2010 new vehicles are not equipped with these technologies. Diesel and hybrid technologies each boost average new car and light truck fuel economy by about 5% in 2010, their smaller impact being due to their smaller market shares.

The sales weighted average impacts of nine classes of fuel economy technologies in the high-efficiency/low-carbon case are illustrated in Figures 5.7 and 5.8. The measured percent fuel economy gain applies to the impact of the technology on the average fuel economy of all new passenger cars or light trucks and, thus, takes into account the estimated market penetration for each category of technologies. In 2010, passenger cars get a considerably greater benefit from engine efficiency improvements than light trucks, but the gap narrows considerably by 2015. Although the DISC and 2-stroke technologies are the most significant new technologies in 2010, the gasoline fuel cell comes on strong by 2015. The impact of the fuel cell in 2010 is obviously limited by the assumption that it would be first introduced in 2007. The impacts shown in Figures 5.7 and 5.8 depend entirely on the cost, fuel economy benefit, and introduction date assumptions shown in Table 5.2, and the way the NEMS model translates those assumptions into market success. Thus, the graphs do not represent a prediction of what specific technologies will achieve, but rather an illustration of what could happen given the outstanding successes in fuel economy technology R&D, as reflected in our high-efficiency/low-carbon scenario assumptions.

The 23% gain for light-duty vehicles in 2015 is just slightly higher than the 21% and 22% improvements by freight trucks and rail in the efficiency scenario. Aircraft efficiency gains seem to lag behind at a mere 9% in 2015, but this is due to the fact that air passenger efficiencies increase the most (17%) in the business-as-usual case. In 2010, rail and air have made the greatest efficiency gains over 1997. This is consistent with the record of the past quarter century, during which time these two modes have led all others in energy-efficiency improvement.

Table 5.7 Transportation Sector Projections to 2010 and 2015 Efficiency Scenario (cont. next page)

	1997	2010		Change v. BAU	
	BAU	BAU	Efficiency	Change	% Change
Energy Use (quads)	25.5	32.3	29.3	-3.1	-9%
Carbon Emissions (MtC/Yr.)¹	487	616	543	-73	-12%
Passenger Cars**	171	184	160	-24	-13%
Light Trucks	113	166	143	-23	-14%
Other Modes	203	266	240	-26	10%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.0	15.2	-2.8	-15%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.5	0.5	***
Distillate	4.6	5.8	5.7	-0.1	-2%
Jet Fuel	3.6	4.7	4.2	-0.5	-11%
Residual	1.2	1.6	1.6	0.0	0%
Other	1.1	2.2	2.1	-0.1	-4%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	18.2	16.3	-2.0	-11%
Passenger Cars**	8.8	9.6	8.6	-1.0	-11%
Light Trucks	5.8	8.6	7.7	-2.0	-11%
Freight Trucks	5.6	6.8	6.3	-0.5	-8%
Air	3.6	4.7	4.2	-0.5	-11%
Rail	0.5	0.5	0.4	-0.1	-16%
Marine	1.7	2.3	2.3	0	0%
Pipeline	0.8	0.9	0.9	0	0%
Other	0.2	0.3	0.3	0	0%
Energy-efficiency Indicators					
New Car MPG ⁺	27.5	27.8	37.5	9.7	35%
New Light Truck MPG	20.5	20.6	27.1	6.5	32%
Light-Duty Fleet MPG	19.6	19.4	21.5	2.1	11%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	58.2	61.6	3.4	6%
Freight Truck Fleet MPG	5.6	6.0	6.8	0.8	13%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.0	3.6	0.6	20%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2762	2774	12	0%
Freight Truck VMT	173	237	238	1	0%
Commercial Air Seat-Miles	1116	1729	1608	-121	-7%
Rail Ton-Miles	1208	1459	1464	5	0%
Marine Ton-Miles	892	1047	1050	3	0%

Note: Because some light truck energy use is included in the freight truck sector, the totals by mode will not add to the totals by fuel type.

⁺ After all scenarios had been completed, a minor error was discovered in the NEMS passenger car fuel economy technology input data. This error allowed four wheel drive improvements to be applied to certain categories of cars to which they are, in fact, not applicable. The overall effect on new car fuel economy is less than 0.3 MPG in 2010 and less than 0.5 MPG in 2015.

** Motorcycles, which are always less than 1%, are included with passenger cars.

Table 5.7 Transportation Sector Projections to 2010 and 2015 Efficiency Scenario (Continued)

	1997	2015		Change v. BAU	
	BAU	BAU	Efficiency	Change	% Change
Energy Use (quads)	25.5	34.0	28.7	-5.2	-15%
Carbon Emissions (MtC/Yr.)	487	646	532	-114	-18%
Passenger Cars	171	192	154	-38	-20%
Light Trucks	113	174	133	-41	-24%
Other Modes	203	280	245	-34	12%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.7	13.5	-5.3	-28%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.4	0.4	***
Distillate	4.6	6.0	6.5	0.5	8%
Jet Fuel	3.6	5.0	4.2	-0.7	-15%
Residual	1.2	1.8	1.8	0.0	0%
Other	1.1	2.5	2.4	-0.2	-6%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	19.1	15.5	-3.6	-19%
Passenger Cars	8.8	10.0	8.3	-1.7	-17%
Light Trucks	5.8	9.1	7.2	-1.9	-20%
Freight Trucks	5.6	7.1	6.3	-0.8	-12%
Air	3.6	5.0	4.3	-0.7	-15%
Rail	0.5	0.5	0.4	-0.1	-20%
Marine	1.7	2.5	2.5	0.0	0%
Pipeline	0.8	0.9	0.9	0.0	0%
Other	0.2	0.3	0.3	0.0	0%
Energy-efficiency Indicators					
New Car MPG	27.5	27.9	41.4	13.5	48%
New Light Truck MPG	20.5	20.6	31.9	11.3	55%
Light-Duty Fleet MPG	19.6	19.5	24.0	4.5	23%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	60.6	66.1	5.5	9%
Freight Truck Fleet MPG	5.6	6.1	7.4	1.3	21%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.2	3.9	0.7	22%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2914	2937	23	1%
Freight Truck VMT	173	250	251	1	0%
Commercial Air Seat-Miles	1116	1923	1759	-164	-9%
Rail Ton-Miles	1208	1535	1540	5	0%
Marine Ton-Miles	892	1099	1102	3	0%

**Table 5.8 Transportation Sector Projections to 2010 and 2015 High-Efficiency/Low-Carbon Scenario
(cont. next page)**

	1997	2010		Changes v. BAU	
	BAU	BAU	HE/LC	Change	% Change
Energy Use (quads)	25.5	32.3	27.9	-4.5	-14%
Carbon Emissions (MtC/Yr.)	487	616	512	-104	-17%
Passenger Cars**	171	184	147	-37	-20%
Light Trucks	113	166	132	-34	-21%
Other Modes	203	266	233	-33	-12%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.0	13.9	-4.2	-23%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.7	0.7	***
Distillate	4.6	5.8	5.7	-0.1	-2%
Jet Fuel	3.6	4.7	4.0	-0.7	-14%
Residual	1.2	1.6	1.6	0.0	0%
Other	1.1	2.2	2.1	-0.2	-8%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	18.2	15.2	-3.0	-17%
Passenger Cars**	8.8	9.6	8.0	-1.6	-17%
Light Trucks	5.8	8.6	7.2	-1.4	-17%
Freight Trucks	5.6	6.8	6.2	-0.6	-9%
Air	3.6	4.7	4.1	-0.7	-14%
Rail	0.5	0.5	0.4	-0.1	-25%
Marine	1.7	2.3	2.3	-0.0	-1%
Pipeline	0.8	0.9	0.9	0.0	0%
Other	0.2	0.3	0.3	0.0	0%
Energy-efficiency Indicators					
New Car MPG ⁺	27.5	27.8	43.1	15.3	55%
New Light Truck MPG	20.5	20.6	30.8	10.2	50%
Light-Duty Fleet MPG	19.6	19.4	23.2	3.8	20%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	58.2	64.6	6.4	11%
Freight Truck Fleet MPG	5.6	6.0	7.0	1.0	17%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.0	4.0	1.0	34%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2762	2806	44	2%
Freight Truck VMT	173	237	238	1	0%
Commercial Air Seat-Miles	1116	1729	1619	-110	-6%
Rail Ton-Miles	1208	1459	1467	8	1%
Marine Ton-Miles	892	1047	1051	4	0%

Note: Because some light truck energy use is included in the freight sector, the totals by mode will not add to the totals by fuel type.

⁺ After all scenarios had been completed, a minor error was discovered in the NEMS passenger car fuel economy technology input data. This error allowed four wheel drive improvements to be applied to certain categories of cars to which they are, in fact, not applicable. The overall effect on new car fuel economy is less than 0.3 MPG in 2010 and less than 0.5 MPG in 2015.

** Motorcycles, which are always less than 1%, are included with passenger cars.

**Table 5.8 Transportation Sector Projections to 2010 and 2015 High-Efficiency/Low-Carbon Scenario
(Continued)**

	1997	2015		Change v. BAU	
	BAU	BAU	HE/LC	Change	% Change
Energy Use (quads)	25.5	34.0	26.7	-7.3	-21%
Carbon Emissions (MtC/Yr.)	487	646	484	-162	-25%
Passenger Cars	171	192	134	-58	-30%
Light Trucks	113	174	114	-59	-34%
Other Modes	203	280	236	-44	-16%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.7	11.2	-7.5	-40%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.7	0.7	***
Distillate	4.6	6.0	6.7	0.7	-12%
Jet Fuel	3.6	5.0	4.0	-1.0	-19%
Residual	1.2	1.8	1.8	-0.0	-1%
Other	1.1	2.5	2.2	-0.3	-12%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	19.1	13.8	-5.3	-28%
Passenger Cars	8.8	10.0	7.4	-2.6	-26%
Light Trucks	5.8	9.1	6.4	-2.7	-29%
Freight Trucks	5.6	7.1	6.2	-0.9	-13%
Air	3.6	5.0	4.1	-0.9	-19%
Rail	0.5	0.5	0.4	-0.2	-38%
Marine	1.7	2.5	2.4	-0.0	-1%
Pipeline	0.8	0.9	0.9	0.0	0%
Other	0.2	0.3	0.3	0.0	0%
Energy-efficiency Indicators					
New Car MPG	27.5	27.9	50.2	22.3	80%
New Light Truck MPG	20.5	20.6	37.8	17.2	83%
Light-Duty Fleet MPG	19.6	19.5	27.1	7.6	39%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	60.6	70.7	10.1	17%
Freight Truck Fleet MPG	5.6	6.1	7.5	1.4	23%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.2	4.8	1.6	51%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2914	2974	60	2%
Freight Truck VMT	173	250	252	2	1%
Commercial Air Seat-Miles	1116	1923	1923	-152	-8%
Rail Ton-Miles	1208	1535	1542	7	0%
Marine Ton-Miles	892	1099	1103	4	0%

Figure 5.7 Sources of Fuel Economy Improvements in High-Efficiency Scenario, 2010

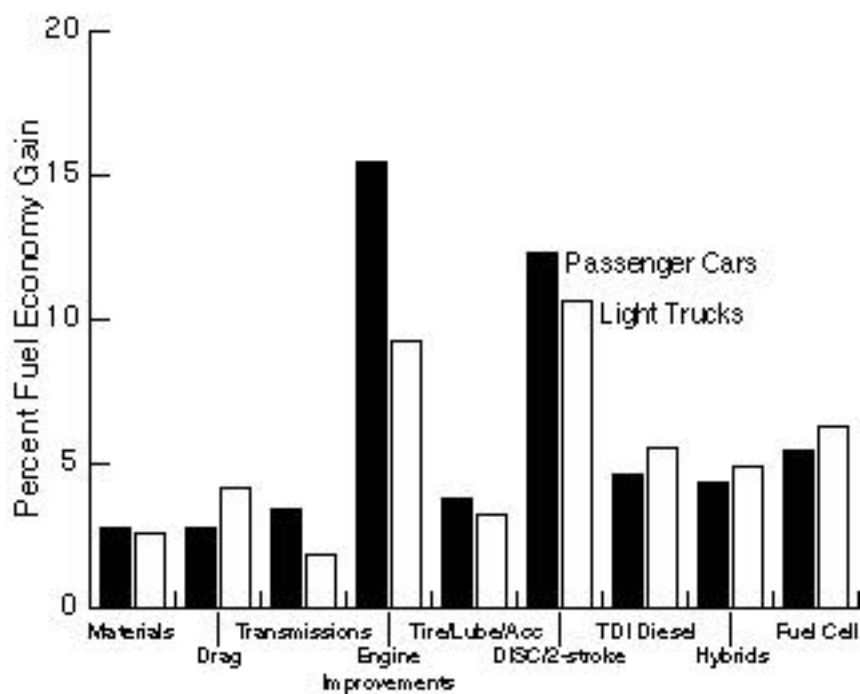
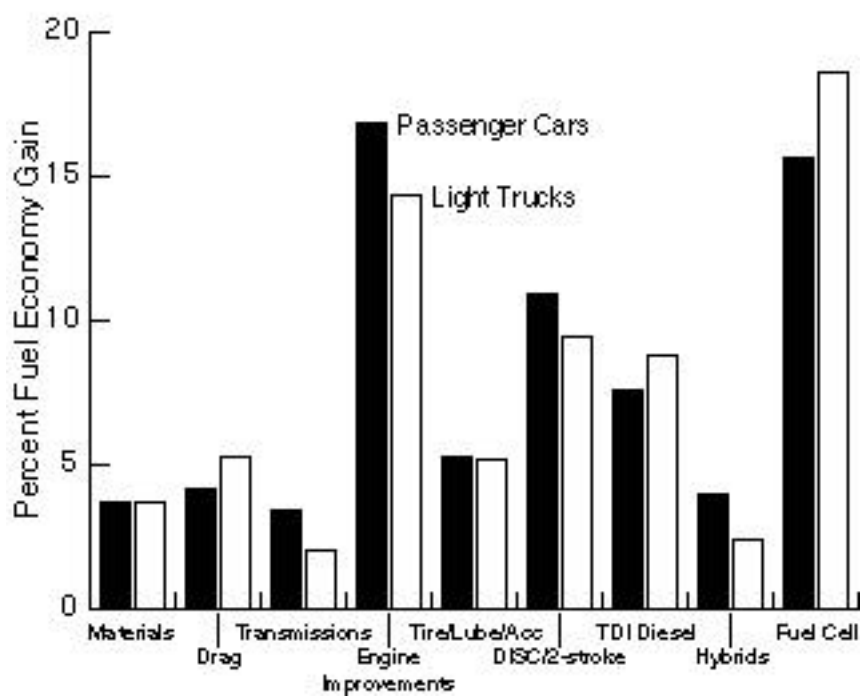


Figure 5.8 Sources of Fuel Economy Improvements in High-Efficiency Scenario, 2015



Transportation activity increases at moderate rates in the business-as-usual case and, indeed, in all the other scenarios as well. Transportation activity in the NEMS model is relatively insensitive to energy prices. In the business-as-usual scenario, light-duty vehicle travel increases by 22% from 1997 to 2010, an average annual rate of just 1.5%. In the high-efficiency/low-carbon scenario, the increase is 24%, reflecting a very small increase due to the lower fuel cost per mile of vehicle travel (1.7%/year). Growth from 2010 to 2015 is slower still, 1.1% per annum. Air travel is the fastest growing mode, with seat-miles growing at 3.4% annually through 2010 and slowing to 2.1% annually from 2010 to 2015. Efficiency improvements in the efficiency and high-efficiency/low-carbon scenarios include increased load factors (passenger-miles per seat-mile) so that seat-miles are actually 7% lower in the efficiency case than in the business-as-usual case in 2010 (Tables 5.7 and 5.8). Freight truck vehicle miles increase at a faster rate than light-duty vehicle miles, 2.5% per year through 2010, slowing to 1.1% from 2010 to 2015. These levels are almost unchanged by further increases in truck freight energy-efficiency. NEMS measures rail and marine activity in ton-miles, and these are up 21% and 17%, respectively, by 2010. Once again, the growth rate from 2010 to 2015 is at the much slower rate of about 1% per year.

The combined effects of moderately increasing transportation activity and significant efficiency gains are still not enough to reduce energy use or carbon emissions below present levels by 2010. Overall, transportation energy use in the business-as-usual case grows from 25.5 quads in 1997 to 32.3 in 2010 and 34.0 in 2015. The efficiency scenario lowers energy use by 9% in 2010 and carbon emissions by an additional 3%, due to the success of cellulosic ethanol as a gasoline blending component. Still, energy use is up 15% over the 1997 level, and carbon emissions are 12% higher. In 2015, however, energy use and carbon emissions are reduced compared to 2010 but still higher than in 1997. Although the 1997 version of the NEMS model does not forecast beyond 2015, it is reasonable to assume that energy use and emissions will continue to fall for a decade or so beyond 2015 as technological improvements penetrate the stock of transportation vehicles.

Motor gasoline use, on the other hand, is only 0.15 quads higher in 2010 than in 1997, and is a full 1.6 quads lower than the current level in 2015. The use of 0.4 quads of cellulosic ethanol and an equivalent shift to diesel are partially responsible for the reduction in gasoline consumption. Because cellulosic ethanol produces almost no net greenhouse gas emissions, it is far more effective than any fossil-based alternative fuel at reducing transportation's carbon emissions. Demand for distillate and jet fuel combined is up 1.7 quads in 2010 and is 2.6 quads higher than the 1997 levels in 2015. The slower growth of gasoline demand suggests a change in refinery operations would be required, but no analysis of the impacts of this change has been made.

The high-efficiency/low-carbon scenario achieves the milestone of reducing CO₂ emissions below 1997 levels, but by 2015 rather than 2010 (Table 5.7). In 2010, CO₂ emissions are 17% (a full 100 MtC per year) below the business-as-usual case, but still 4% above 1997 levels. With new cars at 43 MPG (EPA test value), new light trucks at 31 MPG, and the fleet average at only 27 MPG (23 MPG onroad), efficiency is improving rapidly and still has a long way to go. New passenger car MPG hits a fleet average of 50 in 2015 in this scenario, buoyed by market shares of 25-30% for hybrid vehicles, and 15-20% for turbo-charged direct-injection diesel vehicles. Two-stroke engines are also popular in this scenario, capturing about one-third of the small-car market. By 2015, all remaining new light-duty vehicles are equipped with DISC engines, the gasoline engine of today having been all but entirely squeezed out by newer technologies.

Yet even the high-efficiency/low-carbon case, with its breakthrough technology assumptions, illustrates how much time it takes to fundamentally change the technology of transportation energy use. Though fleet average light-duty vehicle MPG is up from 19.6 to 27.1 (onroad) by 2015, there is another 10.3 MPG to go before the fleet achieves equilibrium with the efficiency of new vehicles. Similarly, in the rail mode, use of fuel cells has penetrated only 5% of the stock of locomotives by 2010 and 15% by 2015. In most cases, the majority of CO₂ emission reductions have yet to be realized, even by 2015. The point is not that little can be done to reduce transportation's CO₂ emissions. The point is that if CO₂ emissions must be reduced, the sooner one gets started, the better.

5.3.5 Cost-Effectiveness of Light-Duty Vehicle Fuel Economy Improvement

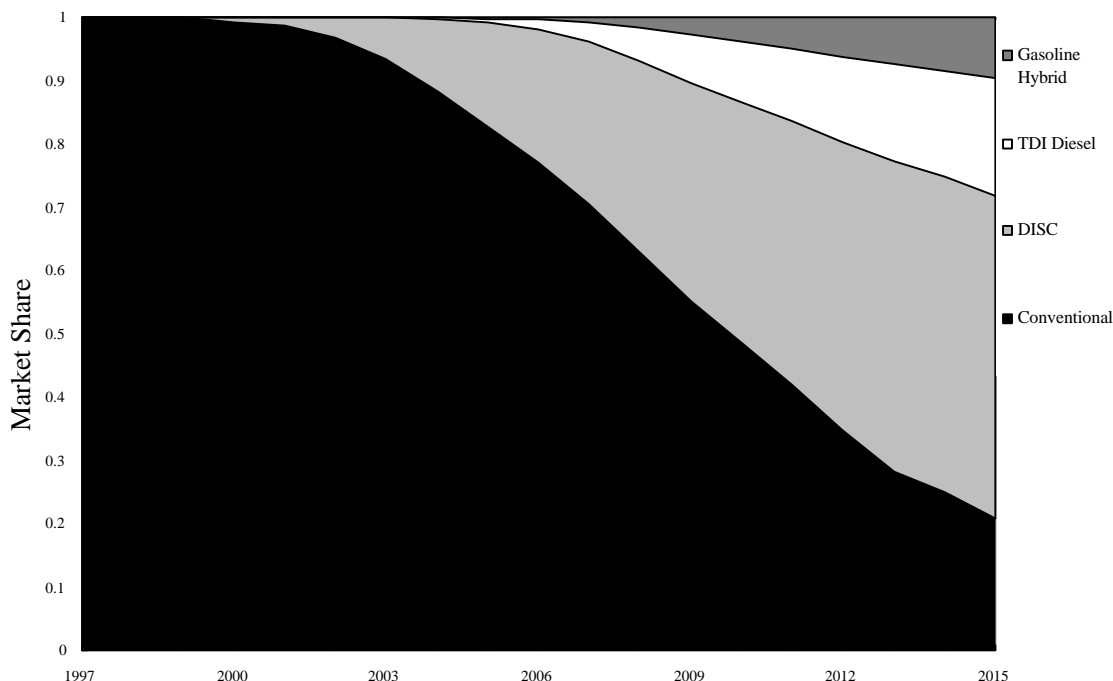
The cost-effectiveness of technological changes that improve fuel economy is a very complex issue, depending not merely on the value of fuel savings and the increase in retail price, but on how each technology affects the performance, reliability, appearance and feel of a vehicle. Even such a seemingly simple matter as computing the value of fuel savings is not straightforward, since it depends on car buyers' expectations about future fuel prices, vehicle lifetime (or, alternatively, market valuation of remaining fuel savings when the vehicle is traded in or resold), consumer discounting of future savings, expectations about future depreciation of the vehicle's value, and expected utilization rates.

Technological advances are likely to create new opportunities to provide other benefits of importance to car buyers and to society. For example, multi-point fuel injection is generally held to be not cost-effective solely on the basis of fuel savings – yet every new car sold and nearly every new light truck is equipped with it. The reason for including fuel injection is that it improves drivability and also is a critical technology for meeting emissions standards. Technologies included in the efficiency scenarios also have the potential to create social benefits. By reducing oil consumption, they will decrease the volume of U.S. oil imports. By making it easier and cheaper to improve efficiency and substitute alternative energy sources for oil, these technologies will improve U.S. energy security. Technologies such as hybrid vehicles and fuel cells will help vehicles meet increasingly stringent emissions standards. Most importantly, technological advances will be essential to creating a sustainable world transport system.

The cost of supplying technologies is also not a simple matter, since it depends on the rate at which capital equipment must be replaced. If the rate of adoption exceeds the normal rate of turnover of manufacturing equipment, the costs of technological change increase. Also, new technologies must often be certified to meet safety and environmental standards, which takes time and involves some degree of risk. Consumers expect a high degree of reliability of vehicles, and this might be threatened by too rapid introduction of novel technologies.

For all these reasons, the NEMS model does not base technology adoption on a simple cost-effectiveness calculation, but rather attempts to simulate the complex process described above. The market penetration of fuel economy technologies is a function of cost-effectiveness, but is not solely determined by it. Market penetration follows an s-shaped curve that predicts 50% market penetration for precisely cost-effective technologies, with increasing or decreasing market share as cost-effectiveness increases or decreases, respectively. This simulates the fact that consumers are not identical in their valuation of technology (e.g., high mileage drivers such as sales representatives might tend to value fuel economy more than would average drivers), and that technologies have other characteristics that consumers may, or may not, value. Also, introduction is not immediate when cost-effectiveness is reached, but is rather phased in over time, simulating a normal process of retirement and replacement of manufacturing capital.

The phasing in of new technologies can be seen in Figures 5.9 to 5.11, which show the predicted market penetrations of engine technologies. Engine technology penetrations in the efficiency case are shown for passenger cars and light trucks in Figures 5.9 and 5.10. Although the DISC, TDI Diesel, and Gasoline Hybrid technologies eventually come to dominate the market, it takes about a decade for this to occur, allowing time for orderly introduction of the technologies. For comparison, the historical market penetration rates of fuel injection technologies are shown in Figure 5.11. Although it took less time for multi-point fuel injection to replace carburetted fuel systems, this technological change was urged on by emissions regulations. Nonetheless, as a point of comparison, it suggests that the rates predicted by the NEMS model are comparable to similar historical transitions.

Figure 5.9 Market Penetration of Advanced Engines for Domestic Passenger Cars - Efficiency Scenario

For all the reasons noted above, simple cost-effectiveness calculations based solely on incremental first cost and the value of future fuel savings can be misleading. Indeed, the NEMS model outputs do not include direct measures of the costs of technological changes or their value to vehicle purchasers. However, for light-duty vehicles, approximate technology cost estimates can be derived from the market shares of each technology and from the initial cost estimates. By comparing the weighted average cost of fuel economy technology in the efficiency and high-efficiency cases in 2010 with the weighted average cost in 1997 for the BAU case, we can obtain an estimate of the increase in retail price per vehicle due to the adoption of fuel economy technology. The incremental costs must be adjusted, however, to reflect the fact that a significant fraction of the potential MPG increase is used in the NEMS model to produce higher horsepower or increased vehicle weight, or to offset small MPG losses due to safety and emissions improvements. The cost adjustment is made by multiplying the full cost increase by the ratio of the actual MPG gain to the potential MPG. For example, for automobiles in the efficiency case, this ratio is 0.7. Using the same assumptions employed in the model to calculate cost-effectiveness, we can also estimate the value to the average consumer of the change in fuel economy. These estimates are summarized in Table 5.9.

Figure 5.10 Market Penetration of Advanced Engines for Domestic Light Trucks - Efficiency Scenario

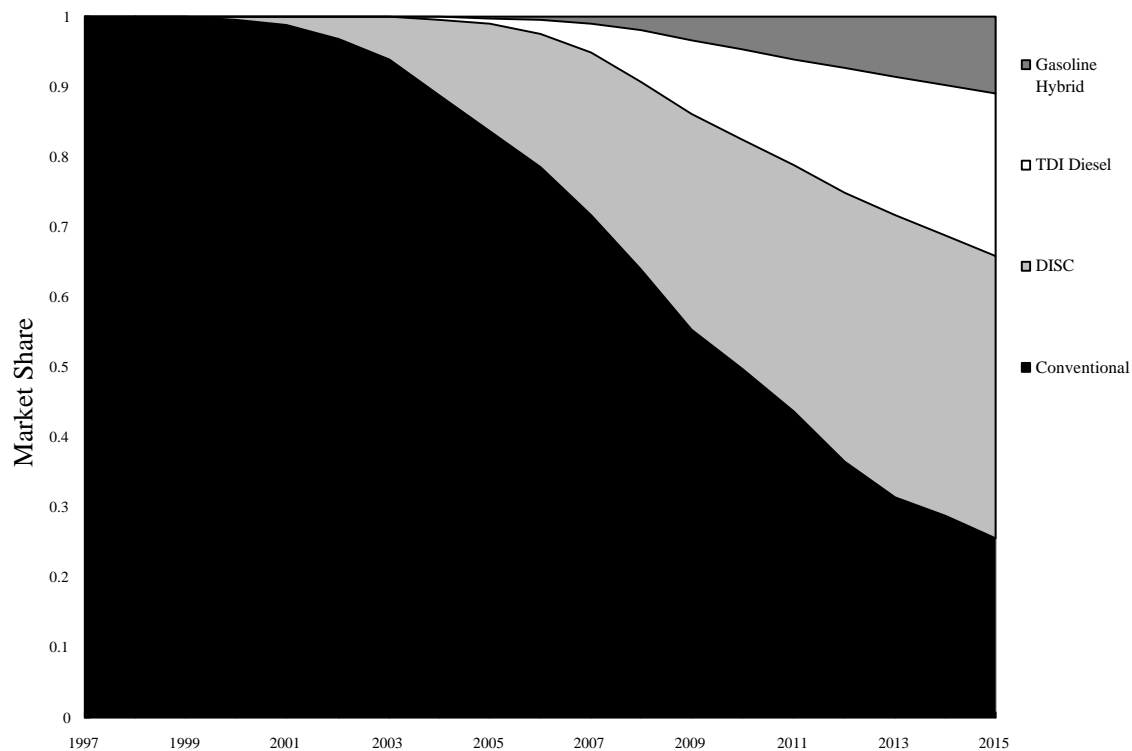


Figure 5.11 Penetration of Fuel Injection Technology

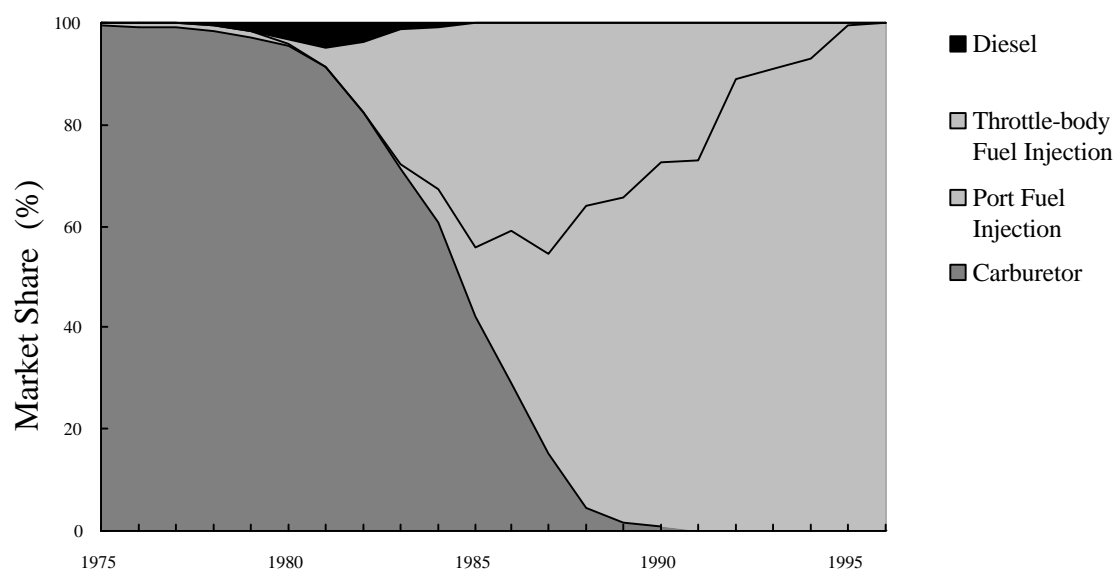


Table 5.9 Simple, Total Cost-Effectiveness Estimates for Light-Duty Vehicle Fuel Economy Technology

Scenario	MPG	Full Incremental Cost	Adjusted* Incremental Cost	Value of Fuel Savings to Consumer	
				10% Implicit Discount Rate	20% Implicit Discount Rate
Passenger Cars					
Business as Usual	27.5	\$0	\$0	--	--
Efficiency	37.5	\$850	\$600	\$1,600	\$1,000
HE/LC	43.1	\$900	\$900	\$2,150	\$1,350
Light Trucks					
Business as Usual	20.5	\$0	\$0	--	--
Efficiency	27.1	\$800	\$650	\$1,950	\$1,200
HE/LC	30.8	\$950	\$900	\$2,700	\$1,700

Gasoline prices assumed to remain constant at \$1.20 per gallon. Vehicle usage rate of 15,500 miles per year, declining with vehicle age at 4% per year, and lifetime of 14 years. For calculating value to consumers, MPG estimates are reduced by 15% to reflect actual operating conditions.

*Adjusted to account for the use of fuel economy technology to increase horsepower instead of increasing miles per gallon.

The cost effectiveness estimates in Table 5.9 show that even at the higher 20% implicit discount rate, the light-duty vehicle fuel economy improvements are, as a whole, cost effective. This is not surprising since the NEMS model bases its technology market penetration predictions on a similar measure of cost effectiveness. Discounting future fuel savings at a lower rate of 10% only improves cost effectiveness.

Based on a simple comparison of incremental vehicle costs to the value of fuel savings to the consumer, fuel economy improvements in the efficiency scenarios appear to be cost-effective as a whole. Savings exceed costs for both discounting formulas shown. Choosing the correct discount rate is somewhat controversial since it depends on whether one believes that there are imperfections in the market for fuel economy. In the buildings chapter, for example, a 7% real rate is used to discount future fuel savings. We believe that a 20% implicit discount rate should be used for valuing light-duty vehicle fuel economy savings for the following reasons. When a consumer invests in vehicle technology to improve fuel economy, his or her decision-making calculus is analogous to a firm's capital investment decision. Indeed, consumers can be thought of as producing their own vehicle travel with inputs of vehicles, materials, and labor. In making this decision, the consumer must not only consider his or her discount rate (time preference or opportunity cost for money) but also the depreciation of capital. In other words, there are two costs of capital that must be accounted for, the time cost of money tied up in the capital and the depreciation of the capital. In general, the depreciation in a car's value is much greater during the first few years of its life. Indeed, a very significant depreciation occurs instantaneously when the first owner takes over possession from the dealer. After that time, the car is no longer "new". The initial owners of vehicles tend to hold them for about four years, on average, so that they bear a disproportionate share of the cost of depreciation.

The tendency of used car markets to "bundle" vehicle attributes, rather than price each separately may create a market imperfection that, when combined with the greater depreciation in value during the first few years of ownership, implies that new car buyers may reasonably be expected to demand a high rate of return in fuel savings for an investment in fuel economy technology. According to this hypothesis, with the exception of a few highly visible items, used car prices are determined by initial prices and the average rate of depreciation. That is, the value of fuel economy in the used car market is determined not so much by the present value of future fuel savings, as by the depreciated value of the initial investment in fuel economy. Assuming this market imperfection exists, the cost to the new car buyer of an investment in fuel economy technology is determined by

the depreciation in its value over the first four years, rather than by the consumption of its fuel savings potential.

The combination of these two factors may lead new vehicle buyers to demand a rate of return much higher than the simple discount rate. If one assumes a 20% depreciation during the first year of vehicle ownership and 10%/yr. thereafter, then a consumer with a 7% real discount rate would, in effect, discount the full 14 years of fuel savings at about 15% to 16% to compensate for the cost of depreciation during the first four years of ownership. If future fuel savings are computed using the average usage rate for new vehicles, then future savings must be further discounted by 4% to 5% per year to reflect the typical rate of decline in vehicle use with age. Taken together, these factors imply that a new car buyer may appear to behave as if his discount rate for valuing future fuel savings were 20%, when in fact his simple real discount rate is only 7%.

These rough estimates should be treated with considerable caution. First, they represent a comparison of total costs of fuel economy changes with total benefits, taxes included, rather than the more correct comparison of marginal costs and benefits, excluding taxes. Markets will, in theory, stop improving fuel economy when the marginal costs equal the marginal benefits. In general, this will be at a lower level of fuel economy than the point at which total costs equal total benefits. Second, the NEMS model represents technology adoption as a more complex process than a simple computation of monetary costs and benefits, and attempts to simulate actual market behavior. Thus, the calculations reported above do not correspond to the NEMS technology adoption methodology.

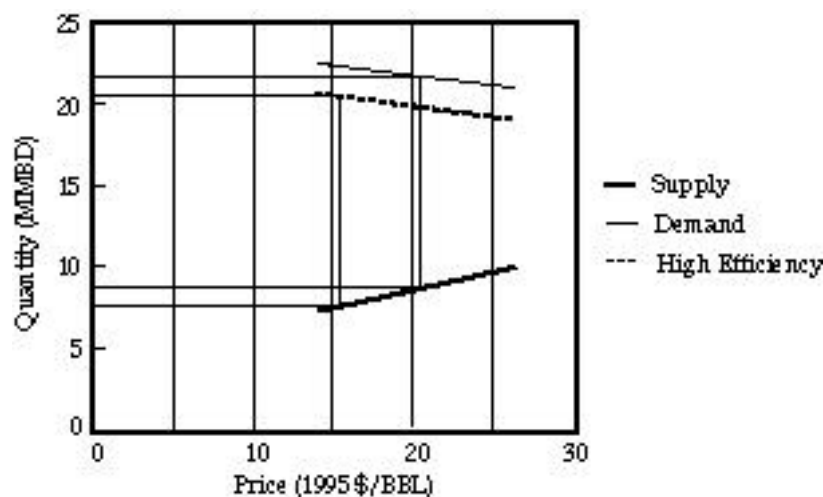
5.3.6 Oil Imports and Oil Market Benefits

The reductions in energy use achieved in the efficiency and high-efficiency/low carbon scenarios represent significant reductions in U.S. petroleum demand which should result in reduced U.S. oil import dependence and lower oil prices to consumers. Because of transportation's continuing dependence on petroleum in the business-as-usual scenario, 95% of transportation energy is still derived from petroleum in 2010. In the BAU scenario, transportation uses 30.6 quads (14.5 million metric barrels per day (MMBD)) of petroleum products. Technological advances contained in the efficiency scenario reduce petroleum consumption by 3.4 quads (1.6 MMBD) in 2010, and those in the high-efficiency/low-carbon scenario produce total oil savings of 4.9 quads (2.3 MMBD).

Lower U.S. oil consumption due to more energy-efficient technology and substitution of cellulosic ethanol should reduce U.S. oil imports, or reduce world oil prices, or both. The exact world oil market response is indeterminate because it depends on the actions of the OPEC cartel. In a competitive world oil market, the response to reduced U.S. demand could be predicted based on knowledge of the U.S. and rest-of-world supply and demand curves for oil. But because the cartel's supply does not necessarily follow the rules of competitive market behavior there is, in effect, no OPEC oil supply curve. Faced with reduced demand, competitive producers would lower prices, encouraging demand and driving out the higher cost producers until a new equilibrium were reached. But a cartel can choose to cut production, raise production, or do nothing, making the ultimate outcome uncertain. Cutting production would raise world oil prices but the cost to OPEC would be loss of market share, a key determinant of market power.

No matter what the OPEC cartel chose to do, however, either U.S. imports would fall, or oil prices would fall, or both, as a result of the technological advances reflected in the efficiency and high-efficiency/low-carbon scenarios. This is illustrated in Figure 5.12, which shows U.S. long-run supply and demand curves for petroleum derived from the 1997 Annual Energy Outlook's Low, High, and Reference Oil Price Cases for 2010 (EIA, 1996b, Table C11). The curves clearly show that at the reference case oil price of \$20.41 per barrel, domestic supply and demand curves do not intersect, with the result that the 12.9 MMBD shortfall must be imported.

Figure 5.12 U. S. Oil Supply and Demand in 2010



The advanced technologies of the high-efficiency/low-carbon scenario shift the demand curve towards lower demand, and may also change its slope (perhaps making demand more responsive to price). If we assume that the world price of oil does not change (to achieve this result, OPEC would have to cut production by an amount roughly equivalent to the reduction in U.S. consumption), then U.S. imports would be lower by about 2 MMBD. If OPEC maintains previous production levels or increases its output, world oil prices would fall. As prices fall, U.S. domestic supply will decline and demand will increase, pushing imports back up. However, to achieve the original level of imports (12.9 MMBD), prices would have to fall by about \$5 per barrel (given the supply and demand curves shown in Figure 5.12). The \$5/bbl. price cut would reduce the total cost of oil to the economy by about \$35 billion, and reduce the cost of oil imports by about \$20 billion, in comparison to the AEO97 reference case. The possible outcomes are: 1) U.S. imports are reduced by 2.3 MMBD or more, 2) world oil prices fall by about \$5/bbl or more, or 3) a combination of reduced imports of up to 2.3 MMBD and a price decrease of up to \$5/bbl. occurs.

5.4 R&D POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020

5.4.1 Light-Duty Vehicles

Many of the advanced technologies that have the potential to impact U.S. automotive fuel use after 2010 or 2020 need considerable research and development work before they can attain commercialization. The federal government has supported work on many of these technologies for more than 20 years, beginning with the Energy Policy and Conservation Act of 1975. The current U.S. R&D effort on the more exotic of the new technologies has been characterized as "the most comprehensive, best organized, and best funded in the world" (U.S. Congress, OTA, 1995). Nevertheless, over the years, federal funding for vehicle technology R&D has been erratic, and there are continuing budget battles over funding for DOE's Electric and Hybrid Vehicle Program and the PNGV as a whole. As noted above, the National Research Council Committee that is reviewing the PNGV program has stated in no uncertain terms that they believe the program is seriously under-funded relative to its ambitious goals.

The OTA identified several R&D areas that will require considerable new resources including: safety; analysis and development of infrastructure for manufacturing, refueling, servicing, recycling, and so forth; and development of new standards for new materials and fuels (U.S. Congress, OTA, 1995). Also, OTA concluded that the current federal program may not take appropriate advantage of the innovative capabilities of small business, especially with budget pressure on the National Institute of Science and Technology's Advanced Technology Program and other R&D efforts that focus on smaller companies.

Although there are many hurdles to overcome, a strong R&D effort coupled with a market or regulatory incentive to improve fuel economy should be capable of producing, by 2020 or earlier, mid-sized vehicles with fuel economies in the 60-80 MPG range and performance similar to current vehicles – that is, "PNGV territory." Note that continuing fleet increases in power and performance will tend to reduce future fuel economy potential, since generally there is a direct tradeoff between performance and fuel economy. An optimistic vision of a potential high-efficiency/low-carbon vehicle in 2020, assuming the necessary breakthroughs in a number of areas (e.g., manufacturing processes for composite materials, two orders of magnitude reduction in fuel cell costs) would combine the following characteristics:

Highly aerodynamic design with C_d of 0.22 or below;

Lightweight body with composite body structure (safer alternative: optimized aluminum);

Ultra-low rolling resistance tires, CR of 0.005 (about half that of today's tires);

Hybrid drivetrain with lightweight, highly efficient storage device (ultracapacitor or flywheel) and electric motor/controller;

Fuel cell powerplant with advanced hydrogen storage or efficient fuel reformer (safer alternatives: DISC engine or DI diesel with lean NO_x catalysts); and

Use of high-efficiency/low-carbon accessories and low-energy-use design (e.g., advanced window coatings and insulation).

The current PNGV program is addressing many of the remaining R&D roadblocks though some need considerably more attention and the solution to others might be accelerated with greater resources. For example, development of manufacturing processes for composites has been hit hard by budget cutbacks; as noted, without major breakthroughs, composites will likely be too expensive to play a major role in vehicle light-weighting. In addition, there is some concern that Japanese and European firms are devoting more resources to DISC and DI diesel engines than are U.S. companies, and these engines may play a critical role in future high-efficiency/low-carbon vehicles, especially if fuel cell development is delayed or is unsuccessful at reducing costs sufficiently for commercialization.

Fuel cells are widely believed to be the most attractive powerplant option for future vehicles, and recent progress in increasing their power density and lowering costs through reducing their platinum requirements has been extremely promising. Nevertheless, as discussed previously, many hurdles remain, and their costs must decline remarkably for them to compete successfully with internal combustion engines. In fact, they would revolutionize the power generation industry long before they reached the \$30/kW level of ICEs.¹⁴

Although some may view a fuel cell hybrid vehicle as an "ideal" vehicle, there are sufficient uncertainties in the potential of the technologies needed for such a vehicle, and sufficient heterogeneity in regional requirements and markets, to imply that an ideal R&D program in light-duty vehicle technologies should be a broad program incorporating a range of alternative technology pathways to high vehicle efficiency and low emissions. A breakthrough in high-specific-energy battery technology coupled with significant progress in electric motors and power electronics, for example, could put large numbers of efficient electric vehicles into many urban markets; in some of those markets (e.g., California) both the overall emissions effects and the greenhouse gas emissions effects could be extremely positive. Similarly, breakthroughs in on-board storage technology for natural gas might allow substantial penetration of natural gas vehicles into many markets, although the positive greenhouse gas emissions impact of such vehicles would likely be substantially less than for EVs or fuel cell hybrids.

5.4.2 Freight Trucks and Locomotives

The diesel cycle engine will dominate the freight truck sector at least until 2020 because of its high thermal efficiency, potential fuel flexibility, and durability. DOE's Office of Heavy Vehicle Technologies (OHVT) within the Office of Transportation Technologies is attempting to develop the enabling technologies needed to achieve fuel flexibility, ultra-low emissions, and high fuel efficiency in all classes of trucks, buses, and other heavy vehicles such as off-highway vehicles. The typical new Class 8 tractor trailer in 2020 is expected to achieve an on-road fuel economy of over 10 MPG, compared to about 7 MPG today, assuming a high-efficiency/low-carbon, low emission diesel cycle engine (thermal efficiency of at least 55% at rated speed and load at the flywheel) and other technologies such as reduced aerodynamic drag, low rolling resistance tires, and lightweight materials (such as magnesium) become an economic reality.¹⁵ While many of these technologies have already been demonstrated to a limited extent, a key enabler is a durable highly efficient NO_x catalyst capable of operating at high-efficiency/low-carbon in an oxidizing atmosphere.¹⁶ Fuel reformulation is envisioned, as well as nonpetroleum fuels, during this period (2000-2020).

However, as the efficiency of the diesel cycle becomes fully exploited (thermal efficiencies of over 63% will be highly unlikely), the hydrogen fuel cell, unconstrained by the Carnot cycle, may be the next powerplant of choice for freight trucks, locomotives, and passenger cars. Significant R&D efforts at DOE have enabled the demonstration of methanol-fueled fuel cell buses and other vehicles. However, significant development of the fuel cell itself, power management strategies, and hydrogen fuel production, distribution and storage are required, and economical solutions are hard to envision before 2020. Particularly problematic are the low cost, efficient production, delivery, and storage of hydrogen fuel (carbon-containing fuels significantly degrade fuel cell thermal efficiency – in many cases to efficiencies below that of current-production diesel engines). The fuel cell powerplant, combined with low aerodynamic drag, low rolling resistance tires, and lightweight materials may raise Class 8 tractor trailer fuel efficiency to 15 MPG or more. Locomotive engines may be an ideal test bed and an early entry for fuel cell powerplant technologies, because sizes needed (4000 hp-equivalent) are on the scale of smaller stationary electrical power generation plants which are already commercial. In addition, locomotives are already driven by computer-driven electric motors for traction control.

5.5 SUMMARY

Cost-effective or near cost-effective technologies and alternative energy sources have the potential to significantly restrain the growth of the U.S. transportation sector's greenhouse gas emissions through 2010. There remains a substantial reservoir of proven technology for improving motor vehicle fuel economy, and technologies that are very nearly market-ready (such as the DISC engine with lean-NO_x catalytic converter) will almost certainly further expand the potential to increase MPG by 2010. New technologies and operational efficiency gains hold out similar potential for air passenger travel and for truck and rail freight. Ethanol derived from cellulosic feed stocks instead of grain could also make a significant contribution by 2010 as a blending component for conventional gasoline if cost reductions foreseen by energy researchers are achieved. Overall, the combined impact of such technologies could be to reduce greenhouse gas emissions by 10% in 2010 and by almost 20% in 2015, relative to the business-as-usual case. If important breakthroughs can be achieved in fuel cells and other key technologies, transportation's greenhouse gas emissions in 2015 could be held below current levels.

In the business-as-usual case, transportation energy use grows from 25.5 quads in 1997 to 32.3 in 2010 and 34.0 in 2015. Carbon dioxide emissions, in million tonnes of carbon, increase from 487 in 1997 to 616 in 2010, and to 646 in 2015. As mentioned earlier, the business-as-usual case anticipates rates of growth in transportation activity that are slow by historical standards. The actual outcome could easily be 10% higher. The efficiency case holds transportation energy use to 29.3 quads in 2010 and 28.7 in 2015. Accordingly, carbon emissions grow to only 543 MtC in 2010 and 532 in 2015. The fact that emissions are lower in 2015 than in 2010 reflects the fact that changing the technology of transportation energy use requires the orderly turnover of durable capital stock. The high-efficiency/low-carbon scenario holds 2010 carbon emissions from transport to 512 MtC, and reduces 2015 emissions to 484 MtC, just slightly below the 1997 level.

Changes in the mix of transportation fuels in the three 2010 scenarios are summarized in Table 5.10. Although petroleum fuels are still the predominant source of energy for transportation, use of alternative fuels expands in all three scenarios. Natural gas consumption for transport grows from 0.75 TCF in 1997 (about 98% of which is used in natural gas pipelines) to roughly 1.2 TCF in 2010. In 2010 pipelines still account for 70-75% of natural gas use, but CNG vehicles consume about 0.25 TCF, and natural gas used to produce methanol for motor fuel accounts for nearly all of the rest. Biofuels in the form of cellulosic ethanol come on strong in the efficiency and high-efficiency/low-carbon scenarios, providing from one-fourth to one-third of an MMBD oil equivalent. In accord with the AEO97 reference case projections, all scenarios foresee substantial increase in electricity use, essentially all going to electric vehicles. The lower levels of electricity use in the efficiency and high-efficiency/low-carbon scenarios, like those of natural gas use, are due to the general improvements in vehicle technology in those scenarios.

Carbon emissions by mode are summarized in Table 5.11. Light-duty vehicles account for the vast majority of carbon emissions reductions versus the business-as-usual case, with significant contributions also being made by trucks and commercial aircraft. Rail freight shows the greatest relative reduction, while emissions from shipping, military and "other" are essentially constant across the three scenarios.

Table 5.10 Transportation Energy Use by Fuel Type

Fuel	1997	2010		
		BAU	Efficiency	High-Efficiency
Petroleum Fuels (MMBD)	11.77	14.59	12.91	12.18
Natural Gas (TCF)	0.75	1.22	1.19	1.16
Biofuels (MMBD OE)	0.001	0.04	0.25	0.34
Electricity (MMBD OE)	0.04	0.23	0.22	0.20

Note: Petroleum fuels converted to million barrels per day oil equivalent using a heat content of 5.738 MMBtu/barrel. Natural gas includes pipeline fuel and natural gas used to produce methanol for use as a neat fuel, but does not include natural gas used to produce methanol for use in Methyl Tertiary Butyl Ether. It is assumed that, to produce one quad of methanol, 1.44 quads of natural gas are required. For electricity generation, 3.38 quads of primary energy are assumed to be required for each quad of electrical energy consumed.

Table 5.11 Carbon Emissions in 2010 (MtC)

	1997	2010		
		BAU	Efficiency	High-Efficiency
Light-Duty Vehicles	278.7	346.3	297.3	273.0
Freight Trucks	73.3	95.0	83.4	80.9
Freight Rail	8.9	9.6	8.1	7.1
Shipping	30.8	42.7	42.3	41.6
Air Transport	60.0	83.5	72.9	69.6
Military, Transit, Other	35.3	39.0	39.3	39.3
TOTAL	486.9	615.9	543.3	511.5

Note: Breakdown into modal carbon emissions based on emissions factors taken from EIA (1996d) and DOE (1996)

Most of the reduction in energy use and carbon emissions comes from light-duty highway vehicles. There are four reasons for this. First, light-duty vehicle technology has been far more intensively studied, so that a great deal more is known about the technological potential for this mode. Second, the level of expenditure on technology R&D is greatest for this mode, with the possible exception of aerospace R&D, including defense aerospace. Third, the commercial modes are believed to be more sensitive to fuel costs and more aggressive in the adoption of energy-efficient technology. Therefore, the rates of energy-efficiency improvement in the business-as-usual case are higher for these modes. Finally, light-duty vehicles simply use more energy than any other mode: 60% in the business-as-usual case. The other modes cannot be ignored, however, and should probably be given much greater attention with respect to R&D investment.

Although technological improvements have the potential to cost-effectively restrain greenhouse gas emissions from transportation, it is not likely that the changes will come about without a major public policy initiative. There are two reasons for this. First, the problems posed by greenhouse gas emissions are what economists term a classical public good externality. This means that the market economy will not provide the right price signals either for the development or the adoption of low-carbon technologies. Second, the AEO97 projections foresee a world where fossil fuels are abundant, available and inexpensive. In particular, none of the oil market upheavals of the past quarter century are present in the forecast. As a result, there are no other economic incentives to encourage either energy-efficiency or alternative fuels. In such an environment, it is not reasonable to expect either that appropriate technology will be developed or that success in the marketplace will result.

As a result, the efficiency case is based on the assumption that policies are implemented to promote the development of cost-effective low-carbon technologies and to spur the adoption of these technologies. In our view, this would include at a minimum a greatly increased public sector investment in R&D addressing energy-efficient and low greenhouse gas technologies, perhaps two to ten times the current level of effort. There are other public interests in developing such technologies (e.g., energy security and environmental sustainability) that, we believe, could easily justify such a level of investment. But policies to insure the adoption of low-carbon technologies in the market would also be necessary. It is not the purpose of this study to recommend what those policies should be; nonetheless, we are obliged to point out that meaningful policies will be necessary.

Indeed, technology has enormous potential to reduce transportation's greenhouse gas emissions. Cost-effective technological change will take time however, and its full effects will not be felt for two decades or more. Because the problems that may result from increased carbon emissions affect the global environment, significant reductions will demand meaningful public policy initiatives. These must include a greater effort to develop low-carbon technologies and a commitment to implement policies that will insure their adoption in the market.

5.6 REFERENCES

- Boedecker, E., J. Cymbalsky, C. Honeycutt, J. Jones, A.S. Kyders, and D. Le. 1996. "The Potential Impact of Technological Progress on U.S. Energy Markets", *Issues in Midterm Analysis and Forecasting 1996*, U.S. Department of Energy, Energy Information Administration, Office of Integrated Analysis and Forecasting, Washington, DC.
- Boeing Commercial Airplane Group. 1995. *Current Market Outlook 1995*, Seattle, Washington, May.
- Borroni-Bird, C. 1997. Chrysler Corp., personal communication, March 14.
- Bowman, D., P. Leiby, and J. Rubin, 1997. "Methodology for Constructing Aggregate Ethanol Supply Curves", Draft report, Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 24, 1997.
- Buchholz, K. 1997. "Chrysler Updates Two-Stroke Engine Progress," *Automotive Engineering*, vol. 105, no. 1, p. 84, January.
- Burke, A.F., 1995. "Electric/Hybrid Super Car Design Using Ultracapacitors," 30th IGCEC Meeting, Orlando, Florida, August.
- California Air Resources Board (CARB). 1991. *Locomotive Emission Study*, Booz-Allen Hamilton, report to ARB, Sacramento, California.
- California Air Resources Board (CARB). 1992. *Evaluation of Emission Controls for Locomotives*, ARB Report, Sacramento, California.
- Cataldi, R. 1995. "Integrating Steel Wheels Into Sustainable Transportation," presented at the *Asilomar Conference on Transportation and Energy*, Pacific Grove, California, Association of American Railroads, Washington, DC.
- Catalysts for Gasoline Fueled European Cars," *Automotive Engineering*, vol. 105, no. 2, pp. 133-135, February.
- Chem Systems, Inc. 1993. *Technical Report Eleven: Evaluation of a Potential Wood-to-Ethanol Process*, DOE/EP-0004, Office of Domestic and International Energy Policy, U.S. Department of Energy, Washington, DC, January.
- Davis, S.C. and D.N. McFarlin. 1996. *Transportation Energy Data Book: Edition 16*. ORNL-6898, Oak Ridge National Laboratory, Oak Ridge, TN.

Decision Analysis Corporation of Virginia. 1996. "NEMS Transportation Sector Model: Documentation Update," Final, Subtask 18-2, prepared for the Energy Information Administration, U.S. Department of Energy, Washington, DC, December.

Delucchi, M.A. 1991. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, vol. 1, ANL/ESD/TM-22, Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois, November.

Delucchi, M.A. 1997. *A Revised Model of Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, University of California Institute of Transportation Studies, February, (Draft).

Energy and Environmental Analysis, Inc. 1994. *Documentation of the Fuel Economy, Performance, and Price Impact of Automotive Technology*, Prepared for Martin Marietta Energy Systems, July.

Energy and Environmental Analysis, Inc., and Decision Analysis Corporation of Virginia. 1996. *NEMS Fuel Economy Model LDV High Technology Update*, Draft Documentation, Subtask 9-1, prepared for the Energy Information Administration, U.S. Department of Energy, Washington, DC, June.

Energy Information Administration (EIA). 1994. *Model Documentation Report: Transportation Sector Model of the National Energy Modeling System*, DOE/EIA-M070, Office of Integrated Analysis and Forecasting, Washington, DC.

Energy Information Administration (EIA). 1996a. *Annual Energy Review 1995*, DOE/EIA-0384(95), Washington, DC, July.

Energy Information Administration (EIA). 1996b. *Annual Energy Outlook 1997*, DOE/EIA-0383(97), Washington, DC, December.

Energy Information Administration (EIA). 1996c. *Alternatives to Traditional Transportation Fuels 1995*, DOE/EIA-0585(95), Washington, DC.

Energy Information Administration (EIA). 1996d, *Emissions of Greenhouse Gases in the United States 1995*, EIA-0573(95), Table B1.

Energy Information Administration (EIA). 1997. *Monthly Energy Review February 1997*, DOE/EIA-0035(97/02), Washington, DC.

"Going with the Wind" 1984. Car and Driver, August.

Greene, D.L. 1992. "Energy-Efficiency Improvement Potential of Commercial Aircraft," *Annual Review of Energy and Environment*, vol. 17, pp. 537-573.

Greene, D.L. 1996a. *Transportation and Energy*, Eno Transportation Foundation, Inc., Lansdowne, Virginia.

Greene, D.L. 1996b. "Commercial Air Transport Energy Use and Emissions: Is Technology Enough?" forthcoming, *Sustainable Transportation: Is Technology Enough?*, American Council for an Energy Efficient Economy, Washington, DC.

Greene, D.L. and Y. Fan. 1995. "Transportation Energy Intensity Trends, 1972-1992," *Transportation Research Record*, No. 1475, Energy and Environment, Transportation Research Board, Washington, DC, 1995, pp. 10-19.

Greene, D.L., 1994. *Alternative Fuels and Vehicles Choice Model*, ORNL/TM-12738, Center for Transportation Analysis, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October.

Greene, D.L., and Y. Fan. 1994. *Transportation Energy Efficiency Trends, 1972-1992*, ORNL-6828, Oak Ridge National Laboratory, Oak Ridge, TN.

- Hadder, G. 1997. CITATION TO COME. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Hattori, et.al. 1990. *A New 5-Speed Automatic Transmission for Passenger Cars*, SAE Paper 900551.
- Heavenrich, R.M., and K.H. Hellman. 1996. *Light-Duty Automotive Technology and Fuel Economy Trends Through 1996*, EPA/AA/TDSG/96-01, Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.
- Jost, K. 1997. "Gasoline-Reforming Fuel Cell," *Automotive Engineering*, vol. 105, no. 2, pp. 51-52, February.
- Leiby, P.N., D.L. Greene, and H.Vidas. 1996. *Market Potential and Impacts of Alternative Fuel Use in Light-Duty Vehicles: A 2000/2010 Analysis*, DOE/PO-0042, Technical Report Fourteen in the Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector, Office of Policy, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, January.
- Lipman, T.E. and D. Sperling, 1997. "Forecasting the Cost Path of an Electric Vehicle Drive System: A Monte Carlo Experience Curve Simulation", Institute for Transportation Studies, University of California at Davis, January.
- Markus, M. 1997. "A Tale of Two-Stroke," *Car and Driver*, March, pp. 115-118.
- McDonnell Douglas, Douglas Aircraft Company. 1996. "Outlook for Commercial Aircraft 1995-2014," Market Planning, Long Beach, California.
- McNutt, B., L. Fulton, and D. Greene. 1997. "Epilogue: Is Technology Enough? A Synthesis of Views Expressed at the Conference" in *Transportation, Energy, and Environment: Can Technology Sustain Us?* American Council for an Energy Efficient Economy, Washington, DC.
- Murrell, J.D., J.A. Foster and D.M. Brister. 1980. "Passenger Car and Light Truck Fuel Economy Trends Through 1980", *SAE Technical Paper Series no. 800853*, Society of Automotive Engineers, Warrendale, Pennsylvania.
- National Research Council, Aeronautics and Space Engineering Board. 1992. *Aeronautical Technologies for the Twenty-First Century*, report of the Committee on Aeronautical Technologies, National Academies Press, Washington, DC.
- National Research Council, Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles. 1997. *Review of the Research Program of the Partnership for a New Generation of Vehicles: Third Report*, National Academy Press, Washington, DC.
- Oei, D-G. 1997. "Fuel Cell Engines for Vehicles," *Automotive Engineering*, Ford Motor Company, February.
- Ogden, J., et al, "Hydrogen as a Fuel for Fuel Cell Vehicles: A Technical and Economic Comparison," National Hydrogen Association 8th Annual Conference, March 1977.
- Roberts, G.F. and D.L. Greene. 1983. *Trends in Heavy Truck Energy Use and Efficiency*, ORNL/TM-8843, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October.
- Ross, M. Et al., 1996. "A Parallel Hybrid Automobile with Less Than 0.1 kWh of Storage," Society of Automotive Engineers, Technical Paper Series, #961282, Warrendale, Pennsylvania.
- Singh, Margaret. Argonne National Laboratory. Personal communications. April/May 1997.
- Strehlau, W., J. Leyrer, E.S. Lox, T. Kreuzer, M. Hori and M Hoffman. 1997. "Lean NO_x
- U.S. Congress, Office of Technology Assessment (OTA). 1995. *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, OTA-ETI-638 (Washington, DC: U.S. Government Printing Office, September.

- U.S. Department of Energy. 1995. *Overview of the U.S. Fuel Cell Program*, DOE ATDCCM, October.
- U.S. Department of Energy, Office of Heavy Vehicle Technologies. 1996. *Office of Heavy Vehicle Technologies Strategic Plan*. Washington, DC.
- U.S. DOE/PO-0042, 1996, *Market Potential and Impacts of Alternative Fuel Use in Light-Duty Vehicles: A 2000/2010 Analysis*, Table D-4.
- U.S. Department of Transportation, Bureau of Transportation Statistics. 1996. *Transportation Statistics Annual Report 1996*, Washington, DC.
- U.S. Department of Transportation, Federal Highway Administration. 1996. *Highway Statistics 1995*, FHWA-PL-96-017, Washington, DC, November.
- Walsh, M., R. Perlack, D. Becker, A. Turhollow and R. Graham. 1997. "Evolution of the Fuel Ethanol Industry: Feedstock Availability and Price", Draft quoted with permission of M. Walsh, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February 12.
- Wang, M.Q. 1996 and 1997. *GREET 1.0 - Transportation Fuel Cycles Model: Methodology and Use*, Argonne National Laboratory, ANL/ESD-33, June 1996, updated in 1997 (GREET 1.2).
- Westbrook, F.W. 1989. "Allocation of New Car Fuel Economy Improvements, 1976-1989: Synopsis," submission to Oak Ridge National Laboratory, November.
- Westbrook, F.W., and Patterson, P.D. (1985). *Dynamics of Light-duty Vehicle Fuel Economy - 1978-1984*, SAE Technical Paper Series 850527.
- Yamaguchi, J. 1997. "Toyota RAV4 EV - Today and Tomorrow," *Automotive Engineering*, February.

ENDNOTES

¹ This rate applies to the period 1973 (18.605 trillion Btus) to 1985 (20.067 trillion Btus). Source is Table 2.2, Monthly Energy Review, April 1997, DOE/EIA-0035(97/04), U.S. Department of Energy, Energy Information Administration, Washington, DC.

² This is a summary report. The full report, which presents this material, was not published due to OTA's closure, but it is now available as part of a three-CD set that contains all of OTA's reports since its inception. U.S. Congress, Office of Technology Assessment, *OTA Legacy: 1972 through 1995*, U.S. Government Printing Office, Washington, DC, Stock no. 052-003-01457-2, \$23 U.S.

³ The Toyota AXV5, with a C_d of 0.20, appears to avoid sacrifices in interior and cargo space. Removing its wheel skirts, which might inhibit maintenance and restrict the vehicle's turning circle, would likely raise its C_d to about 0.22. Because the vehicle's underbody cover adds weight, the net positive effect on fuel economy will be reduced somewhat (U.S. Congress, OTA, 1995).

⁴ In particular, requirements for 0-60 mph acceleration and sustained gradeability.

⁵ Also referred to as compression ignition direct injection (CIDI) engines and turbocharged direct injection (TDI) diesel engines.

⁶ Also referred to as compression ignition direct injection (CIDI) engines and turbocharged direct injection (TDI) diesel engines.

⁷ An accurate cost comparison would have to account for the transmission needed by the engine versus the electric motor needed to convert the fuel cell's output electricity into shaft power. Also, the fuel cell drivetrain may need a powerful battery to drive the vehicle until the cell can warm up.

⁸ At about 3700 psi storage pressure, storage volume for hydrogen is about 5 times that needed for gasoline (Oei, 1997).

⁹ An additional cost may be the loss in system efficiency associated with onboard reforming as well as the original refining of the gasoline. However, onboard hydrogen storage has energy costs in the form of hydrogen production (probably at a large scale, and more efficient than the onboard reformer) and pressurization if stored in high pressure tanks.

¹⁰ Despite what is implied in the NEMS Transportation Model documentation, we were informed by Mr. David Chien, principal in charge of the Transportation Model, that the model's calculations were in 1987\$. Thus, \$8 in 1995 dollars equates to approximately \$6 in 1987 dollars.

¹¹ For carbon only; or \$.08-\$0.16 per gallon if the tax applies to all greenhouse gases, on a carbon equivalent basis.

¹² Communication from Margaret Singh of Argonne National Laboratory, April 3, 1997. Her calculations were made using the August, 1993 version of M. A. Delucchi's greenhouse gas emissions model and exclude any vehicle efficiency gains which might occur with the use of an ethanol vehicle.

¹³ An alternative approach would have been to introduce these technologies using the Transportation Model's alternative fuel vehicle capabilities. This approach was not taken on the grounds that diesel is more conventional than an alternative fuel. Consumers are familiar with it, it is widely available and, especially for the advanced, clean, TDI technology considered here, its performance would be essentially identical to that of a gasoline vehicle.

¹⁴ Actually, for an accurate comparison, an ICE plus a transmission and inexpensive fuel tank should be compared with a fuel cell, hydrogen storage or liquid fuel storage/reformer system, battery for warmup power and power buffer, and electric traction motor, making the task of commercializing fuel cells all the more onerous.

¹⁵ The Class 8 truck is very efficient already. Considering an energy per ton-mile measure of performance, an equivalent passenger car needs to travel about 140 miles on a gallon of gas to be as efficient as a 7 MPG Class 8 truck.

¹⁶ This technology is required for direct-injection gasoline engines as well.